Establishing the European Geological Surveys
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for Europe

RESOURCE Project

Deliverable 5.2

Detailed conceptual hydrogeological models for pilot areas and case studies

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SUMMARY

Work package 5 (called CHAKA) of GeoERA RESOURCE project focuses on typologies for karst and chalk areas. Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with a complicated regime that includes both fast flow routes that makes them vulnerable to pollution, and slow baseflows of older uncontaminated water that mixes at the springs and wells. This complexity and heterogeneity of groundwater flow in karst aquifers limits the use of classical methods applied to porous aquifers for assessing the water reserve volume or evaluating their vulnerability. Classically, due to the high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy to characterize the karst as a whole. Usual karst classifications rely on these measurements according to available time series data. Resource-WP5 will test and evaluate monitoring and interpretation methods to come up with an improved characterization framework and typology that will be tested on pilot areas across Europe.

The methodology proposed in WP5 consists of applying several data treatment tools to time series data measured in various karst case studies. Task 3 (5.3) of WP5 is dedicated to the elaboration of the WP5-database of time series on a set of karst case studies from the various European countries participating in WP5.

The present report constitutes the deliverable 5.2 of RESOURCE project, describing the various case studies and available time series data brought by EurogeoSurveys participating in WP5. The objective of this deliverable is to provide a description of each case study on which time series data analysis will be carried out. Finally, the information provided by time series data analysis will be compared to the characteristics of the case studies in order to calibrate/validate such tools and the associated classification and therefore verify if these methodologies are well suited to characterize and classify chalk/karst aquifers.

One section is dedicated to the description of each case study. It is organized according to the following subsections: (1) Overview, (2) Geology, (3) Geomorphology, (4) Climate, (5) Hydrogeology, (6) Hydrodynamic characteristics of the springs, (7) Data available for the project, (8) Summary, (9) References.

The available time series data in these case studies will be treated using the various existing analysis methods described in Deliverable 5.1. An intercomparison of these results will be carried out in order to identify the most appropriate and simple methods which are useful for characterizing the resources and vulnerability of studied chalk and karst aquifers. These results will be described in Deliverable 5.3 of the project.

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1 INTRODUCTION

1.1 Context : Work Package 5 - CHAKA

Work package 5 (called CHAKA) of GeoERA RESOURCE project focuses on typologies for karst and chalk areas. Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with a complicated regime that includes both fast flow routes that makes them vulnerable to pollution, and slow baseflows of older uncontaminated water that mixes at the springs and wells. This complexity and heterogeneity of groundwater flow in karst aquifers limits the use of classical methods applied to porous aquifers for assessing the water reserve volume or evaluating their vulnerability. Classically, due to the high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterize the karst systemas a whole. Usual karst classifications rely on these measurements according to available time series data. Resource-WP5 will test and evaluate monitoring and interpretation methods to come up with an improved characterization framework and typology that will be tested on pilot areas across Europe.

A first report constituting the deliverable 5.1. of RESOURCE project, describing the state of the art of karst aquifers typology and conceptual models in karst hydrogeology, has been produced by CHAKA team in January 2020.

1.2 Content of the deliverable

The methodology proposed in WP5 consists of applying several data treatment tools to time series data measured in various karst case studies. Task 3 (5.3) of WP5 is dedicated to the elaboration of the WP5-database of time series on a set of karst case studies from the various European countries participating in WP5. The present report constitutes the deliverable 5.2 of RESOURCE project, describing the various case studies and available time series data brought by EurogeoSurveys participating in WP5. The objective of this deliverable is to provide a description of each case study on which time series data analysis will be carried out. Finally, the information provided by time series data analysis will be compared to the characteristics of the case studies in order to calibrate/validate such tools and the associated classification and therefore verify if these methodologies are well suited to characterize and classify chalk/karst aquifers.

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Section 16 is a summary describing the wide range of the characteristics of the various karst aquifers studied in this project.

Appendix 1 of the report contains a series of one-slide descriptions of the case studies that can be used for communication purpose.

2 CROATIA: GACKA RIVER SPRINGS

2.1 Overview

The catchment of the Gacka River is situated in the western Croatia, within the Lika region. The Western half of Croatia is a part of the broader Dinaric karst area which spreads parallel to the eastern Adriatic coast over the territories of several countries from Italian border across SW Slovenia, Croatia, W Bosnia and Herzegovina and Montenegroto to the N Albania. The area is characterised by pronounced karst morphology, absence of surface water on elevated plateaus and mountains, and occurrences of large karstic springs at their foothills

Gacka river springs at four major and several smaller (intermittent and permanent) karstic springs situated along the SE border of the Gacko polje (lowland) area. The river naturally flows for aprox 30 km in NW direction across relatively flat karst polje surface. The river has branched into two main branches and sank completely in several sinkholes at the foothills of the karstic massif which separates the polje from the Adriatic sea.

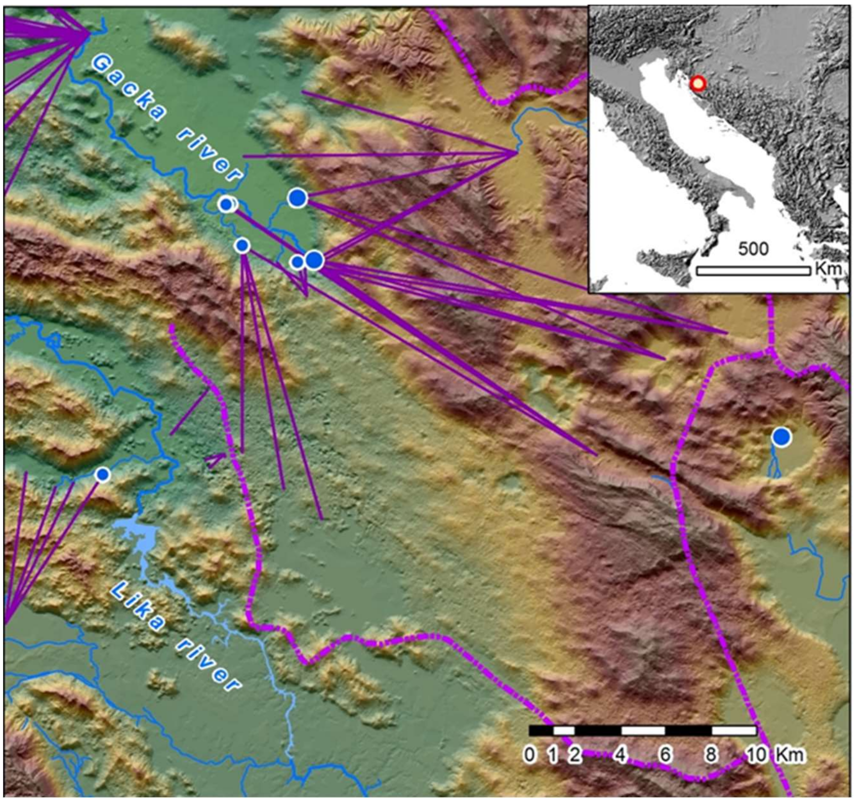


Figure 1: Gacka catchment area is located in the western part of Croatia within the broader Dinaric karst region (water tracing connections marked with solid lines; approx. catchment boundary with dashed line).

Nowadays Gacka River is utilized for electric power production, and the watercourse is diverted in the downstream part through a tunnel to the hydroelectric plant located on the sea coast. In present conditions natural sinkholes of the river are active only during extremely high waters, or during service works on the tunnel, on average only a few days a year.

Intake facility for the public water supply of the Gacko polje and its surroundings (approx. 10.000 inhabitants) is located on the one of the main Gacka springs. Mean yearly pumping rates amounts approx. 50 l/s, which is negligible compared to minimum discharge of the spring (approx. 1000 l/s). However, Gacka springs are designated as a strategic water resource, and planned for future public water supply of the much broader area.

Beside energy production and public water supply, the Gacka River is important for tourism, especially trout fishing, and there are also fish farms located on the river. The Gacka River and its immediate surrounding is included and protected as an important bird habitat within Natura 2000 ecological network of the European Union.

The catchment of the Gacka springs (slightly over 500 km^2) is very scarcely populated, with total number of inhabitants in the range at approx. 1500. There is no significant industrial activity within it, and the main economic activity is extensive cattle breeding, mainly sheep and cows. The majority of the area is covered with woods, and in lesser extent with the pastures, while only a fraction is cultivated lands. Themajority of the catchment area is protected within sanitary protection zones for public water supply.

2.2 Geology

Various carbonate rocks, susceptible to karstification, underlie almost the entire catchment area of the Gacka river. Non-karstifiable Eocene marls appear only on a limited area (few km^2) on the SE margin of the catchment. Dolomitic rocks of Jurassic age prevail in the NE part of the catchment. Cretaceous limestones and in less extent dolostones build up the central and SE parts of the catchment. SW and W part of the catchment, together with Gacko polje area on which Gacka river flows, is built of well-lithified and compact Tertiary carbonate (mostly limestone) breccias. These breccias are thoughtt to originate from intensive rock fracturing during tectonically most active phases of structural formation of External Dinaride Mountains, most likely lasting from the end of Eocene to the beginning of Miocene period. The breccias are non-layered and less fractured compared to the older (Messosoic) carbonate rocks. This results in pronounced solutional morphology of terrains built up of the breccias with scarce soil and debris cover on the surface. Soil cover is mostly continuous on dolomitic terrains, while on limestones it is usually discontinuous with numerous outcrops of the bedrock. Nevertheless, even on dolostones cover is usually thin, typically few tens of cm thick. Only in karst depressions, which appear more frequently on limestone terrains, soil cover could be few meters thick.

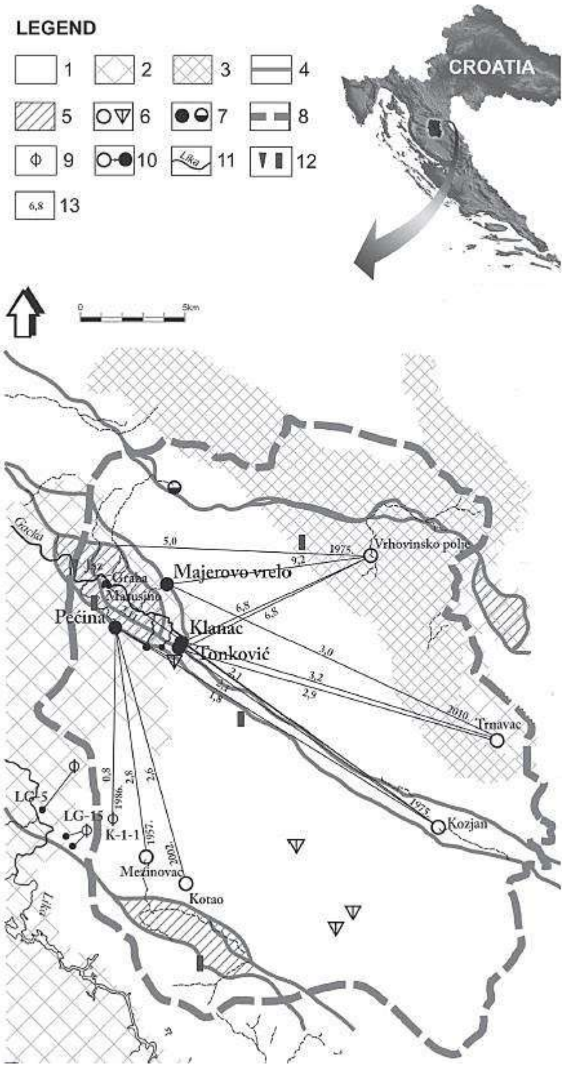


Figure 2: Schematic hydrogeological map of the study area.
1– prevailing limestone rocks, 2– carbonate breccia, 3–prevailing dolostone rocks, 4– most important faults, 5– extension zone, 6– swallow hole (ponor) and vertical cave (pit), 7– spring: permanent and intermittent, 8– groundwater divide, 9– borehole, 10– groundwater connection (tracer test), 11– river, 12– river and rain gauge stations, 13– groundwater velocity determined by tracing tests (cm/s) (modified from Lukač Reberski et al. 2013).

2.3 Geomorphology

The catchment area of the Gacka River can be described as a hilly karst area which surround large flattened surface of the Gacko polje on which the Gacka River flows. Mountainous area E and SE from the polje is the most elevated part of the catchment (1000-1200 m a.s.l.), while the lowest part is the Gacko polje which is on 450 m a.s.l. Karst plateau intersected with numerous dolines and with elevations mostly within 600-700 m a.s.l. forms S and SW parts of the catchment. Besade Gacko polje, there are a few much smaller karst poljes on higher elevations (600-800 m a.s.l.) on the E and S parts of the catchment. Watercourses in these poljes are not permanent, i.e. dry up during dry periods of the year. Sinkholes of these watercourses were used to perform groundwater tracing tests, based on which the catchment boundaries are defined.

2.4 Climate

Mean annual temperatures within the catchment area are within 5-10 °C, while mean annual rainfall ranges 1200-1500 mm/y (www.meteo.hr). Locally, the relief plays a key role in the definition of climate conditions. Temperature is lowering and precipitation is generally higher with increasing elevation, so lowest temperatures characterize mountainous E part of the catchment. Minimum rainfall is usually in summer (July as the driest month average 70 mm of rainfall) and most intensive precipitation is during autumn (November precipitation average 170 mm). The climate is generally of continental type but modified by the maritime influence of the Mediterranean. Highest parts of the catchment characterise a mountain climate that differs primarily by lower air temperature and snow cover regime. Snow cover last 30-100 days in average, depending on the elevation.

2.5 Hydrogeology

The Gacka River catchment is a typical karstic system where water is flowing mainly through underground solution conduits, while permanent or intermittent surface watercourses are present only in areas of karst poljes. Surface elevations of karst poljes are typically within oscillation amplitude of groundwater level in surrounding area. Where and when surface elevation is below groundwater level karst springs appear, while where groundwater is bellow surface level sinkholes appear. Estavelles, spring-sinkhole features, which function depends on hydrological conditions, i.e. on the groundwater level in surrounding massif, are typical manifestation of surface water-groundwater interrelation on karst poljes.

The only permanent surface watercourse in the area is Gacka River, which is fed by four major and more minor springs situated along the SE borders of the polje. The river is flowing across the polje surface towards sinkholes located on the NW polje borders. Eastavellas appear along the river course between the spring and the sinkhole areas. Formerly, in natural conditions the complete river sank in the sinkholes and reappeared on the surface at numerous coastal springs along Adriatic coast. Direct distance between the sinkholes and the coast is approx. 20 km, but the water sinking in sinkholes emerges on the springs spread across 70 km of coastline.

Two of the main springs (Majerovo and Pećina springs) have human enterable openings to the conduit network feeding them. Morphology of the explored conduits shows complex looping morphology with frequent channel branching and changes from horizontal to steeply inclined passages. Majerovo spring is explored to the maximum depth of -104 m below spring level, and total length of explored passages is 950 m (www.ddiskf.hr). This confirms that conduit network is developed to at least to 100-150 m bellow the polje level.

Springs and watercourses of a few higher elevated and much smaller karst poljes within the catchment are typically active only during wet periods. Tracing tests of the sinkhole located in these poljes defined the catchment boundaries. Apparent groundwater velocities of the injected tracers were mostly within 1-10 cm/s range, without obvious relation to the geology, i.e. limestones, dolostones or breccias building the area between the sinkholes and springs. That points to well-developed conduit networks in both limestone and dolomite rocks despite less pronounced surface karst morphology on dolomitic terrains. Transition from the zone of permanent springs to the zone of estavellas in the Gacko polje is abrupt and probably caused by barrier function of the major fault stretching along the W border of the polje (*Figure 1*).

Based on the catchment morphology and elevation of the springs, thickness of unsaturated zone ranges from 0 to approx. 800 m. Maximum depth of the hydrologically active conduits within the system is largely unknown, but based on the results of speleo-diving explorations in the wider area it should be presumed to be at least 200 m bellow low water levels. Geological boundary with non-karstic rocks is at much greater depth, so it is not relevant for estimation of the lower boundary of karstification.

There are neither deep wells nor piezometers within the Gacka catchment, so water levels within the system are estimated based on natural water occurrences, i.e. springs, estavellas, and sinkholes (ponors). An attempt to capture water through borehole in the (closer) hinterland of the Tonković and Klanac spring was a failure due to a very low yield of the borehole. This indicates very low effective porosity of rocks surrounding karst conduits, which is general characteristic of compact Mesozoic carbonate rocks of Dinaric karst.

Gacka springs generally have high water quality. Water quality is regularly monitored only on the public water supply spring, but some data for other main springs is also available (e.g. Matić et al. 2016). Rare events of increased turbidity, usually followed by increased bacterial content, present the only problem for water supply purposes. These events typically happen only during extremely high-water conditions, and last only for a few days. Turbidity and bacterial content increases in high water conditions are a natural phenomenon typical for karst springs, and they are not connected (directly) to the human activities within the catchment. There are no other contaminations documented for the Gacka springs.

2.6 Hydrodynamic characteristics of the springs (and river)

Mean annual discharge of the Gacka River downstream from the main springs amounts approx. 15 m^3/s. Minimal recorded discharge is slightly above 2 m^3/s while maximum recorded discharges are up to 70 m^3/s. This points to relatively good regulation capacity of the karst system, compared to other big karst systems in Dinaric karst area where minimum/maximum discharge ratios are usually less favourable. On average lowest discharges are during summer (August and September), while highest are during autumn and spring (November, December and April). Minimum recorded discharges are related to the occasional draught periods that extended from summer to autumn months (October, November).

There is generally no reliable long-term discharge data for individual springs, except from Tonković spring (public water supply spring) on which hydrological station is located. However, some data is available based on monitoring and measurements carried through various former projects. Presently, there is ongoing project carried by Croatian Geological Survey which includes two-year monitoring of the main springs dynamics. Concerning individual spring dynamics, Majerovo spring and Tonković spring (captured for the public water supply) are the most abundant in draught periods, while other two major springs, Pećina and Klanac springs, dry up during most severe drought periods. The most pronounced discharge variations are typical for the Pećina spring, indicating lowest storage and regulation capacity of SW part of the catchment, largely built of carbonate breccias. Lukač et al. (2013) estimated that 29% of the total Gacka river discharge originates from the Tonković spring, 26% from the Klanac spring, 24% from the Majerovo spring, 15% from the Pećina spring, and 6% from all the other springs. The estimation was based on two-year monitoring period of individual springs during 2008-2010.

2.7 Data available for the project

1. Majerovo spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 hour	1.5 year	05/2018-01/2019
Electrical conductivity	1 hour	1.5 year	05/2018-01/2019
Temperature	1 hour	1.5 year	05/2018-01/2019
Major anions/cations	1 month	1.5 year	05/2018-01/2019
O, H stable isotopes	1 month	1.5 year	05/2018-01/2019
TOC	1 month	1.5 year	05/2018-01/2019

*unreliable data

2. Tonkovića spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 hour	1.5 year	05/2018-01/2019
*Discharge	1 day	>30 years	1982-2016
Electrical conductivity	1 hour	1.5 year	05/2018-01/2019
Temperature	1 hour	1.5 year	05/2018-01/2019
Major anions/cations	1 month	1.5 year	05/2018-01/2019
O, H stable isotopes	1 month	1.5 year	05/2018-01/2019
TOC	1 month	1.5 year	05/2018-01/2019

*unreliable data

3. Klanac spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 hour	1.5 year	05/2018-01/2019
Electrical conductivity	1 hour	1.5 year	05/2018-01/2019
Temperature	1 hour	1.5 year	05/2018-01/2019
Major anions/cations	1 month	1.5 year	05/2018-01/2019
O, H stable isotopes	1 month	1.5 year	05/2018-01/2019
TOC	1 month	1.5 year	05/2018-01/2019

4. Pećina spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 hour	1.5 year	05/2018-01/2019
*Discharge	1 day	20 years	1997-2016
Electrical conductivity	1 hour	1.5 year	05/2018-01/2019
Temperature	1 hour	1.5 year	05/2018-01/2019
Major anions/cations	1 month	1.5 year	05/2018-01/2019
O, H stable isotopes	1 month	1.5 year	05/2018-01/2019
TOC	1 month	1.5 year	05/2018-01/2019

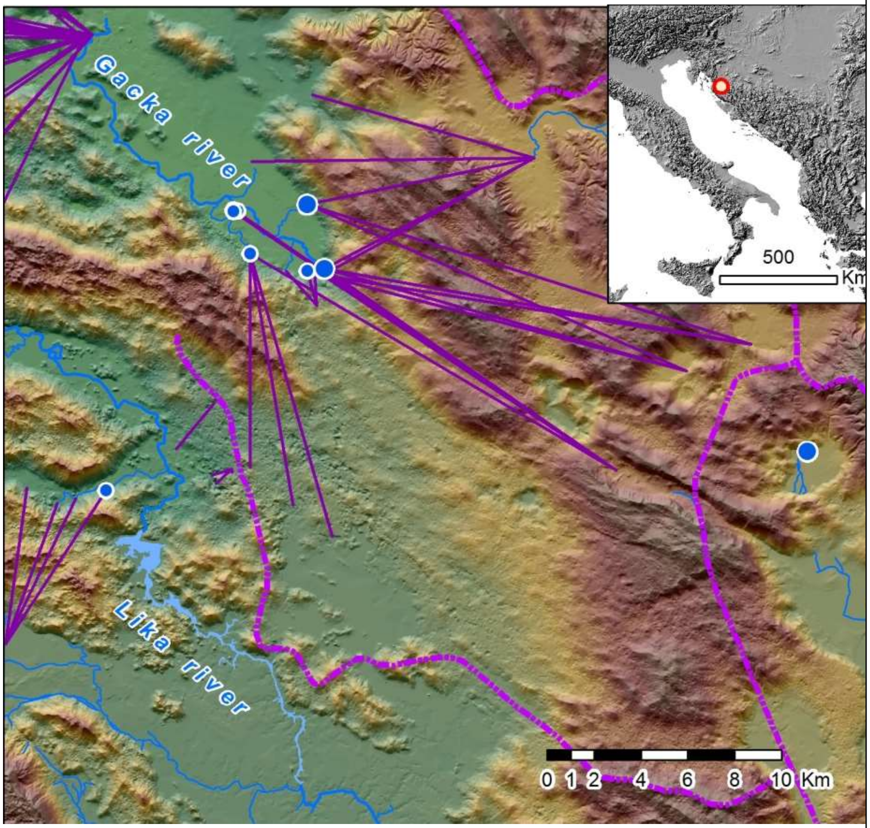
*unreliable data

5. Grab spring			
Data type	Time step	Monitoring period	Time period

Discharge	1 hour	1.5 year	05/2018-01/2019
Electrical conductivity	1 hour	1.5 year	05/2018-01/2019
Temperature	1 hour	1.5 year	05/2018-01/2019
Major anions/cations	1 month	1.5 year	05/2018-01/2019
O, H stable isotopes	1 month	1.5 year	05/2018-01/2019
TOC	1 month	1.5 year	05/2018-01/2019

5. Gacka river (joint discharge of all spring)			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	>20 year	1995-2016

2.9 Summary

Pilot name	**GACKA RIVER SPRINGS**		
Country	Croatia	EU-region	Mountain areas
Area (km^2)	515	Lithology	Limestone & dolomite
Short description: Karst springs of the Gacka sinking river are situated in western part of Croatia within broader Dinaric karst region, There are four major and several smaller springs with a total discharge ranging 2-70 m3/s, Catchment area of springs is situated within well karstified and scarcely populated mountainous area (450-1300 m a.s.l.). Complete catchment is composed exclusively of karst rocks: limestones and dolomites.			
Monitored objects	River; springs (five)		
Monitored data	Discharge, temperature, EC, chemistry, isotopes		
Contact person	Andrej Stroj (astroj@hgi-cgs.hr)		

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3 FRANCE: FONTAINE DE NÎMES

3.1 Overview

The Nîmes city has been forever subject to catastrophic floods events. History of the city mentions about 42 flood events from 1334 to 2005, about one flood every 16 years on average. Almost 60 % of the events happen during the three months between September and November. In the recent past, the most important one occurred on 3 October 1988 and killed 9 people among 45,000 disaster victims (Fabre, 1990). Damages were about 600 x 10^6 euros. The specific maximum outflow discharge (q) of the Cadereaux rivers, defined as Q/A, where A is the surface catchment area (42 km^2) and Q is maximum estimated discharge (1600 m^3/s in 1988), is equal to 38.1 $m^3/s/km^2$, the highest in a comparative study done by Stanescu and Matreata (1997) on flash floods along rivers in five European countries. These flash floods have been for a long time considered to be the result of very intensive rainfall events from Cevennes climate influence conjugated with the geomorphologic context (Ballais et al., 2005) of the city which is located at the bottom of a hill. Usually, overland flow tends to play the dominant role in flash flood formation and low infiltration capacity is the most important factor for overland flow development. However, with a very scarce and thin soil cover of high infiltration capacity, karstified limestone of Nîmes hills are in theory favourable to the infiltration of a part of rainwater, reducing the potential overland flow genesis. Therefore, soils characteristics in the watershed are such that flash flood should not happen in Nîmes city.

The Fontaine de Nîmes (FdN) spring is located in South-Eastern France, in the city of Nîmes. Most of the time, it constitutes the only discharge point of a karst system which is famous for its rapid reaction to rainfall events. The unsaturated zone is maximum ten meters thick and the saturated zone is limited to a few tens of meters. A well developed karstic network drains the aquifer to the FdN spring (*Figure 3*). Part of these drains have been mapped by speleologists during several diving explorations.

3.2 Geology

From a geological point of view, this basin consists of a succession of east-west oriented folds; the aquifer formations that are the site of underground flows are mainly the carbonate formations of the Upper Hauterivien, several hundred metres thick.

Karst has developed mainly within the limestones of the Upper Hauterivien (n3b). There are many karst phenomena on the surface: swallow holes, caves and losses attest to the intense karstification of the limestone massif. The drains of the karst network upstream of the spring, explored by speleologists, are large in diameter, allowing large flows. They are divided into two main branches:

- the western network on which the Poubelle well is located, whose large diameter suggests significant water circulation;
- the northern network on which the well of the 9 Arcades is located in the Cadereau d'Alès ("Eau Bouillie" district). With a smaller diameter, the flows seem less important.

The geological history of the Nîmes karst does not allow us to consider a very deep extension of the karstification, because it has been crossed out for a large part of its history, particularly during the Messinian crisis. A development of the karst system under the main network is limited to a few tens of meters. This karstifiable potential certainly does not exceed 100 meters.

At the outlet, the spring is located at the level of the geological contact between the limestone massif of the Garrigues and the plio-quaternary sediments, including the Piedmont silts. This contact more or less coincides with the position of the Nîmes Fault, which, through its normal fault displacment, caused the southern compartment to drop, bringing the limestones into contact with the plio-quaternary sediments.

3.3 Geomorphology

The city is located at the bottom of the hill at the convergence of three temporary streams called "cadereaux", which is a local term designating the small valleys around Nîmes traversed very temporarily by torrential flows during rainy events: the Uzes stream from the east, the Ales stream from the north and the Camplanier stream from the west (*Figure 3*). These streams are monitored for their discharge by the City services in order to organise the alert and manage the emergency services during flood crisis.

3.4 Climate

The climate is Mediterranean (or dry summer climate), characterized by rainy winters and dry summers, with very little precipitation (less than 40 mm) for at least three summer months. The average temperature is 13.8°C. The area receives around 740 mm annual precipitation that recharges the karst aquifer mainly by diffuse infiltration and swallow holes.

3.5 Hydrogeology

The karst basin (*Figure 3*), defined by numerous tracing experiments (Fabre, 1997) and a water budget calculation (Maréchal et al., 2005), is estimated to be on the order of 55 km^2. The area is quite urbanised in the southern part and covered by natural Mediterranean vegetation (Garrigues) in the north. The catchment area is mainly composed of limestone from Hauterivian, Cretaceous.

The springs of the system consist of the FdN spring, with a discharge between 0.01 and 18 m^3/s, and several intermittent springs discharging only during flash floods.

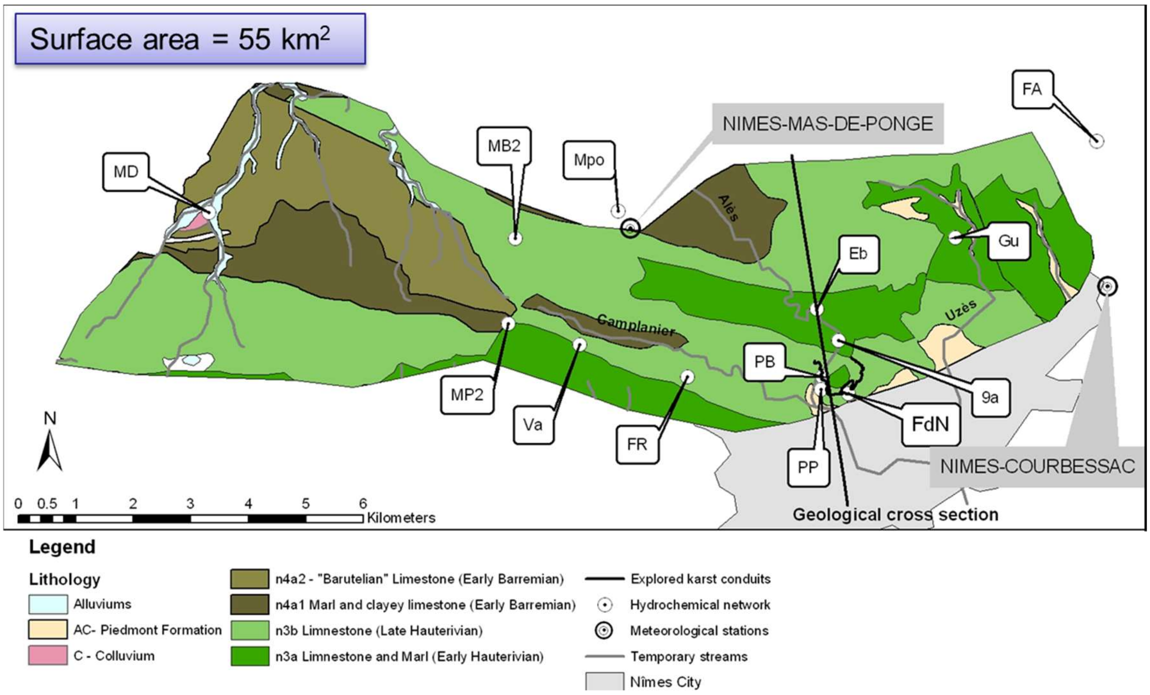


Figure 3: Hydrogeological basin of Fontaine de Nîmes karst system (location of the main spring (FdN) and other springs or wells monitored for hydrochemistryanalysis)

The groundwater table has been monitored during an inondation event thanks to a network of water level recorders located in observation wells. The evolution of water levels shows that the fissured system (out of karst conduits – in wells) has been saturated on 6th and 7th September a few hours after the first event: rate of groundwater rising ranges between 0.2 and 0.5 m/h. The small fissures are quickly filled by groundwater. During the second event, the infiltrated water could not be stored in the karst and therefore contributed to the surface runoff. Local flooding effects are also observed where geomorphology is favourable, in local depressions for example. The fast saturation of the fissured karst is due to its small storage capacity partly explained by the little thickness (1 – 10 meters) of the unsaturated zone as shown by small water table depths in wells before the event.

This saturation of the fissured karst system induces many intermittent springs located in the whole karst basin. It appears that these springs were discharging and the fissured karst was saturated while the water level in the conduits network was much deeper (Poubelle well in Figure 6). This means that, in this case, the fissures are not saturated by water from the karst conduits as observed in other cases by hydraulic inversion (Marina Bay, Bonacci et al., 2006) but by water infiltrating directly on its shallow part characterized by extreme fracturing, the epikarst. Geochemical information makes it possible to consolidate these interpretations.

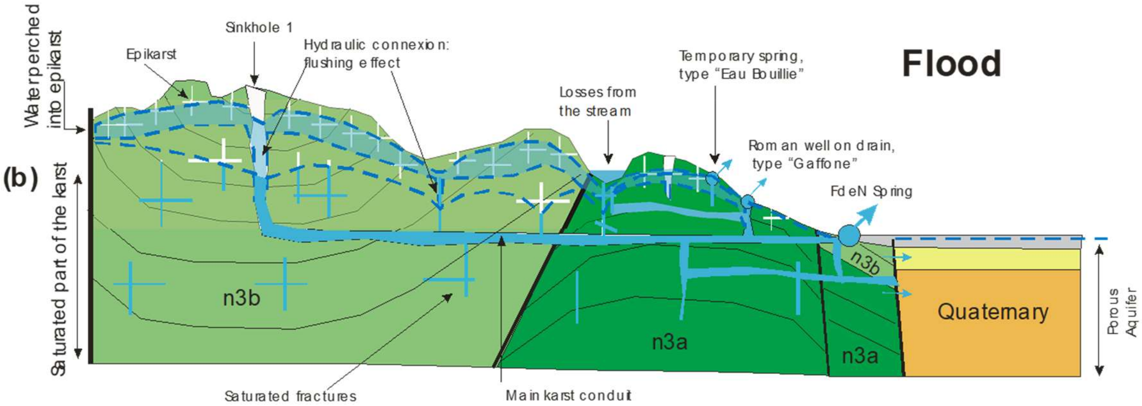


Figure 4: schematic hydrogeological cross-section of Fontaine de Nîmes karst aquifer during high flow conditions

3.6 Hydrodynamic characteristics

Examination of the sorted discharge rates diagram of the FdN spring on a long period (1998-2005) shows that during high flood periods (Q > 13 m^3/s), the slope of straight line $\alpha3$ is superior to $\alpha2$ (*Figure 5*). When discharge exceeds 13 m^3/s, hydraulic properties of the hydrosystem change (slope break): the discharge rate at the main spring increases less quickly. This is typical of the participation of intermittent overflow springs to the total discharge of the system: therefore, the discharge at the main spring increases less because water is flowing elsewhere.

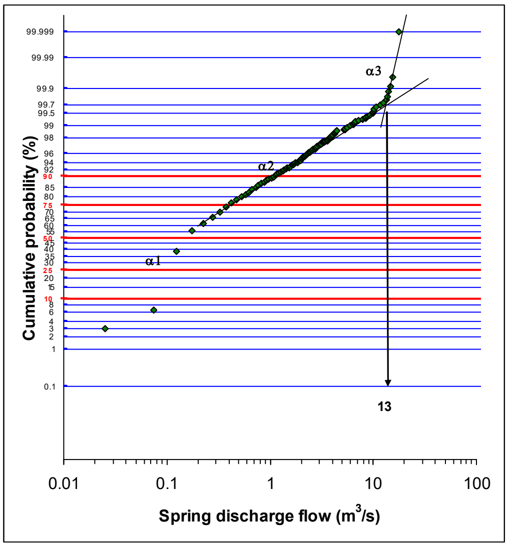


Figure 5: Sorted discharge rates of FdN spring during 1998-2005 period (0.05 m^3/s class)

Some of these intermittent springs are very close to the known conduits network with which they are directly connected. An example (*Figure 6*) is a Roman well and a sinkhole which flood with significant discharge rates (as an example, 1.4 m3 s-1 on 7th September and 2.2 m^3/s on 9th September; Jouanen, Personal Communication). This flooding should be due to backup of excess flow behind a constriction in the major conduit leading to the spring: this phenomenon is known in karst hydrology as backflooding (Lowe and Waltham, 2002). Indicators of flow inversion (diving rope displacement) have been observed by speleologist divers in the conduit after large floods (Jouanen, Personal Communication). This backflooding induces sinkhole flooding and large intermittent springs upstream of the city, which contribute to the flood.

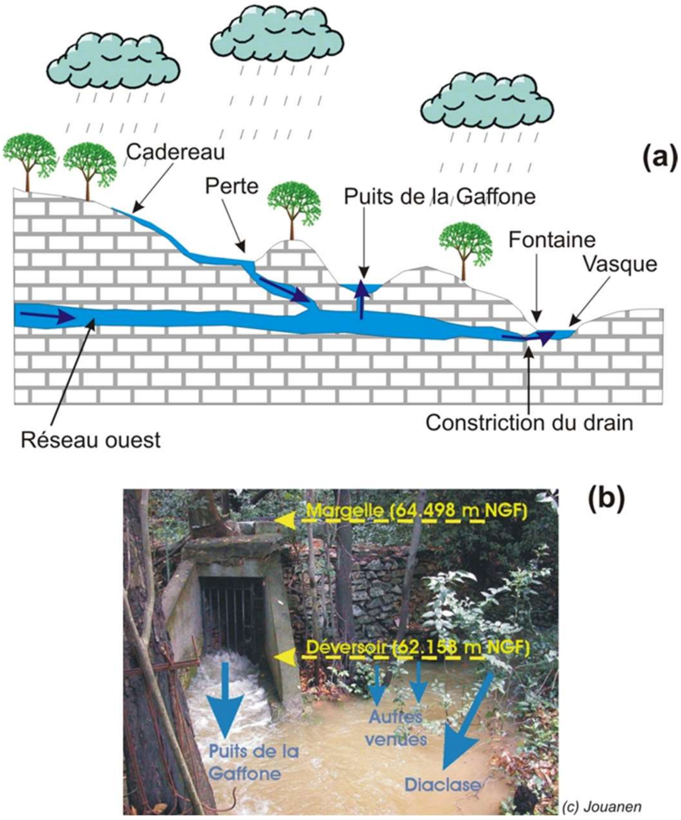


Figure 6: Inverse flow recorded in a Roman well and a sinkhole during 9th September event, due to backflooding (© G. Jouanen, Association Fontaine de Nîmes)

With a catchment area of 55 km^2 and a maximum estimated discharge of 30 m^3/s in 1988, the specific maximum outflow discharge qM is equal to 0.55 $m^3/s/km^2$, one of the highest compared to other karst springs studied by Bonacci (2001) in Croatia, France, USA and Yugoslavia. The limited discharge capacity of FdN spring is coherent with a previous analysis (Bonacci, 2001) which considers that karst springs with qM < 1 can be classified as those with limited discharge capacity.

3.7 Data available for the project

This is a SNO Karst observatory: http://www.sokarst.org/index.asp?menu=cinq_obs
Hydrodynamic and physico-chemical measurements recorded at the spring, in surface water (cadereaux, which are dry streams used to channel rainwater), in boreholes or in cavities, augmented by geochemical campaigns have made it possible to describe the mechanisms responsible for the genesis or attenuation of flash flooding in the Mediterranean karst environment (Maréchal et al. 2008; Maréchal et al. 2009). Numerical modeling has improved flood forecasting (Fleury et al. 2013). Complementary tracing tests have also been conducted (Maréchal et al. 2010). The network of hydrodynamic monitoring rests on the following data:

- Discharge (8 hydrometric stations on the 5 cadereaux and 1 station at the Fontaine de Nîmes)
- Piezometry (8 piezometric stations)
- Pluviometry (9 rain gauge stations)
- Hydrochemistry (spatial campaigns on the drainage basin)

Since 2012, the measuring system has been enhanced by a fluorimeter that continuously (every 15 minutes) measures variations in natural fluorescence associated with the transport of dissolved natural organic and particulate matter. This continuous monitoring is supplemented by spatial campaigns making it possible to quantify Total Organic Carbon and to define the spectral signature (3D excitation/emission matrix) of fluorescent compounds.

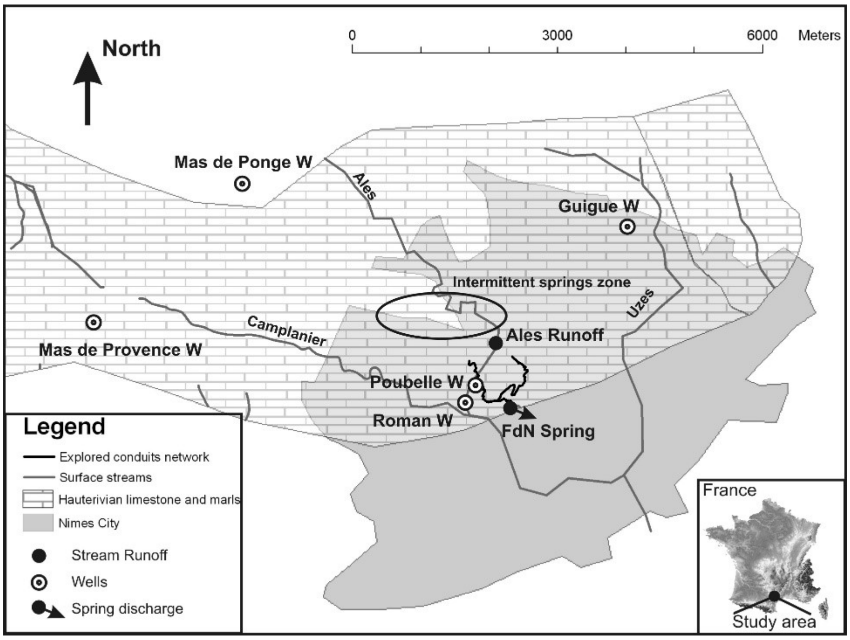
The objective of this work is to:

- Describe the dynamics of organic contaminant transfer in a karst system, using the strong anthropic signal on this system,
- Define new indicators of rapid infiltration in a karst environment to describe better the qualitative state of the water and spring pollution vulnerability.
- Determine the relationship (non-linearity, seasonal effects, etc.) between natural fluorescence and the water's organic content.

1. FdN spring			
Data type	Time step	Monitoring period	Time period
Discharge	15 minutes	22 years	1998-2020
Electrical conductivity	15 minutes	22 years	1998-2020
Temperature	15 minutes	22 years	1998-2020
Major anions/cations	Monthly	3 years	2004-2007
Turbidity, fluorescence	15 minutes	3 years	2019-2022

*unreliable data

3.8 Summary

<table>
<tr><td>Pilot name</td><td colspan="3">**Fontaine de Nîmes Spring**</td></tr>
<tr><td>Country</td><td>France</td><td>EU-region</td><td>Mediterranean</td></tr>
<tr><td>Area (km^2)</td><td>55</td><td>Lithology</td><td>Limestone</td></tr>
<tr><td>Short description: Fontaine de Nimes spring is the main outlet of a Mediterranean karst system (55 km2) close to the coast. Located North of Nimes city, its fast reaction to rainfall induces floods. A part of the catchment being occupied by thousands of inhabitants, the monitoring of fluorescence and TOC has been used in order to trace quick flow components during rainfall.</td><td colspan="3">


</td></tr>
<tr><td>Monitored objects</td><td colspan="3">Spring (one), wells (two)</td></tr>
<tr><td>Monitored data</td><td colspan="3">Discharge, temperature, EC, chemistry, isotopes, fluorescence</td></tr>
<tr><td>Contact person</td><td colspan="3">Vincent Bailly-Comte (v.bailly-comte@brgm.fr)</td></tr>
</table>

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4 BOSNIA AND HERZEGOVINA: VRELO BUNE SPRINGS

4.1 Overview

The spring of Buna is located in the south of Bosnia and Herzegovina, not far from Mostar. The source is located in the area of the Dinaric karst, which runs SW-SE from Slovenia, through Croatia and Bosnia and Herzegovina to Montenegro and Albania. The area is characteristic by pronounced karst morphology, absence of surface water on elevated plateaus and mountains, and occurrences of large karstic springs at their foothills. „Vrelo Buna“ is one of the most famous and largest springs in the Dinarides. It is formed at the contact of Cretaceous limestone and Eocene flysch, at an altitude of 64 m. The basin area is estimated at more than 1100 km^2.

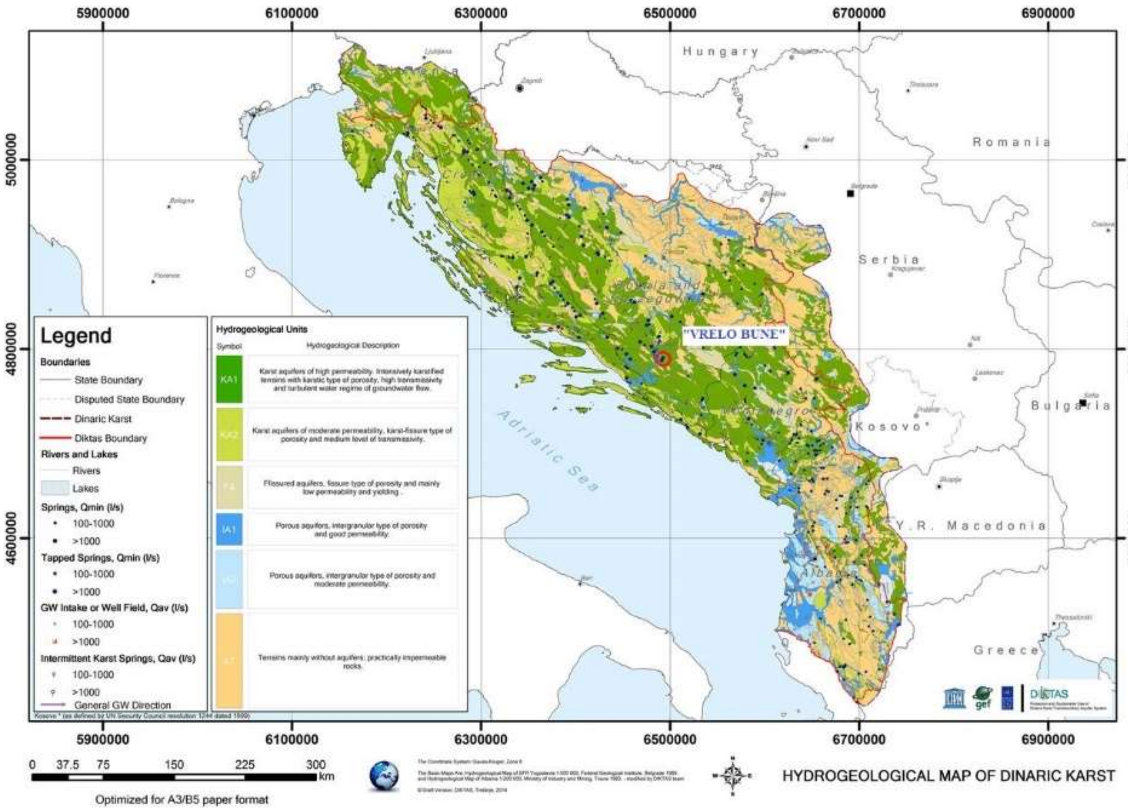


Figure 7: The position of the “Vrelo Buna” in the Dinaric karst

4.2 Geology

The catchment area of the “Vrelo Buna” basin is built mainly by the carbonate cretaceous of the through which there are discordantly deposited clastic deposits of Eocene. Only the bottom of the Nevesinje field are deposits of alluvial deposits found.
The lower cretaceous ($K_{1,2}$) is predominantly dolomite and limestone with, a total thickness of about 700 m. The upper cretaceous (K_2) is built mostly of limestone and subordinate dolomite and dolomite limestone. The total thickness of the upper chalk is about 1000 m. Chalk deposits of over 1500 m thick have the most important hydrogeological role because they are very cracked and karstified, and represent an aquifer that drains on the “Vrelo Buna”.
The Eocene deposits are discordant through Cretaceous deposits; alveolin-numulative limestones of the lower-middle eocene ($E_{1,2}$); deposits of middle-upper eocene ($E_{2,3}$) built of sand, marl, conglomerate and clay, and conglomerates of oligomiocene (E, Ol). These Eocene deposits have an important hydrogeological function of hydrogeological barriers, especially in the case of cretaceous deposits. The total thickness of eocene sediments is about 500 m.
Quaternary sediments are represented mainly by the glowing alluvial layers of gravel, sand (al) in the Nevesinje field. Their thickness is less than 10 m.

4.3 Geomorphology

In the geomorphological view, the “Vrelo Buna” catchment area is located in the area which, belongs to the area of the Dinaric mountain system. The Dinaric mountain system is orientated in the northwest-southeast direction, characterized by the greater part of the southern branch of the Alpine Mountain Wreath. The Dinaric mountain system is characterized by deep river valleys and canyons, large karst fields and mountain ranges with heights from about 1,000 to over 2,000 m. The larger mountains in the Vrela Buna Basin are Velež, Crvanj, Bjelašnica-hercegovacka, Baba, and others.

The special geomorphologic features of the terrain in the Vrela Buna basin are large karst fields among which the Nevesinje field stands out.
One of the special features of the terrain in the “Vrela Buna” basin, which is of decisive importance for the overall hydrogeological relations of this area, is a large area of karst terrains. In limestone, which are mostly built by mountains, fields and plains in the catchment area of Vrelo Buna, various surface and underground karst forms have been formed. From the karst forms, there are many kindergartens, bays, squares, fields, dry valleys, occasional floating fields, and other forms, and from underground sinks, caves, and karst springs. In addition to the occurrence of many karstic forms, one of the important characteristics of the mountains in these terrains is the absence of river flows on the surface, and the water-mobility of karst aquifers in the interior of carbonate masses that empties over strong karst springs at the foot of the mountains. In the area of the Nevesinje field, the built-in flysch sediments of Eocene, the river Zalomka appears, and other smaller occasional watercourses that, after a short flow, are lowered into karst terrains.

4.4 Climate

The catchment area of the “Vrelo Buna” has a sharp mountain climate with long cold winters and short warm summers. There is a very pronounced influence of the Mediterranean climate where due to the geomorphologic features of the Dinaric Mountain System collide warm and cold air masses that bring great precipitation in the catchment area. The mean annual air temperature is 12.3 - 15.3 ° C. Precipitation is unevenly distributed; from 1,135 mm in the lower Neretva stream to 3,124 mm on karst plateaus of high mountains and Nevesinje polje. Climatic conditions, in addition to hydrogeological relations, are of crucial importance for the formation of enormous water wealth, as well as the water regime that is emptied on the “Vrelo Buna”. Maximum precipitation is from April to May, and from September to November, and minimum from July to September.

4.5 Hydrogeology

Hydrogeological relations

The catchment area of the “Vrelo Buna” is largely composed of the permeable rocks of the cavernous-cracking porosity of the Cretaceous, and the predominantly impermeable complexes of the Eocene. The permeable rocks with cavernous-cracking porosity are limestone. The Limestone is fractured and very karstified; good water conductivity and porosity. These rocks have hydrogeological functions of an aquifer. The aquifer is characterized by the flow of groundwater to favoured directions and karst channels. It is distinguished by its high-water conductivity and the flow rate of groundwater.

Non-permeable rocks in the catchment area of the “Vrelo Buna” are predominantly impermeable complexes of Eocene. Non-permeable rocks have functions of lateral, and partly roof hydrogeological barriers. The Upper Cretaceous are locally entrenched on the deposits of the Eocene, which together with the dolomites of the Upper Cretaceous, most likely caused the appearance of the "Buna" spring.

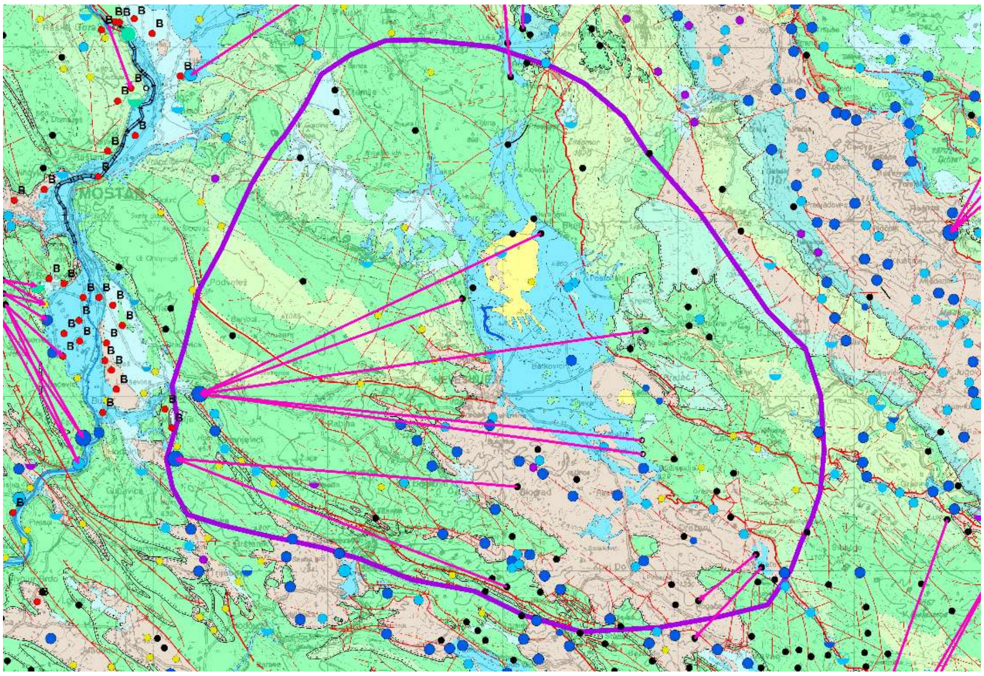


Figure 8: Hydrogeological map of the catchment area of the “Vrelo Buna” spring

The catchment area, sources and accumulations of groundwater

The “Vrelo Buna” spring watershed area is defined by hydrogeological research and tracer testing. The “vrelo Buna” spring is mostly concentrated through the sinkholes in Nevesinjsko polje, and diffused from karst massifs of Velež, Crvanj and Hercegovačka Bjelašnica. The catchment area of the “Vrelo Buna” Buna spring is about 1100 km^2.

Directions and speeds of the flow of underground waters were determined by tracer studies, from sinks in the Nevesinjsko polje, Trusina and Hansko polje.

According to the Vrelo Buna spring, the waters that sink in the Zalomka basin flow, from the Kifino selo to the estavela Ždrebanik, then the waters that sink in the Zovidolka cove, before flowing in Zalomak (estavela Ćetanuša). The part of the catchment area of Vrelo Buna which includes the sails of the northwest part of the Nevesinje field with the most significant sinks Ždrijelo, Baba and Zlatac has an area of 98 km2. And the connection of these sinks with the "Vrelo Buna" has been repeatedly confirmed. The catchment area "Vrelo Buna" also belongs to the mountainous area between the Nevesinje field and the spring (Podveležje massif and parts of Velež).

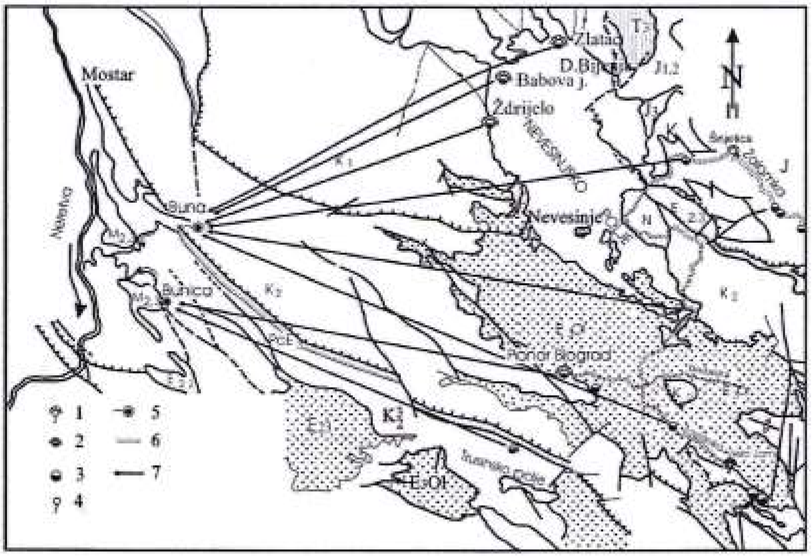


Figure 9: Directions of the flow of groundwater in the catchment area "Vrelo Buna"

The very strong underground connection with the "Vrelo Buna" has been demonstrated by the sinking of the Zlatac, Zdrile, Zalomke sands, the Žljebovi and Ždrebanik boreholes. The fictitious circulation velocities of the boiling water are of the order of v = 4 cm / sec (approx. 3400 m / day).

The spring of the "Vrelo Buna" (*Figure 10*) is certainly one of the most famous and most attractive springs in the Dinaric karst. The spring has a concentrated outlet from the cave, and according to the latest research, the upward spinning mechanism (deep siphon boiling). According to a study by C. Touloumdijian (2001), 470 m of the Buna sifon channel was explored. The depth of the excavated part of the siphon is -78 m (in relation to the place of the dive).

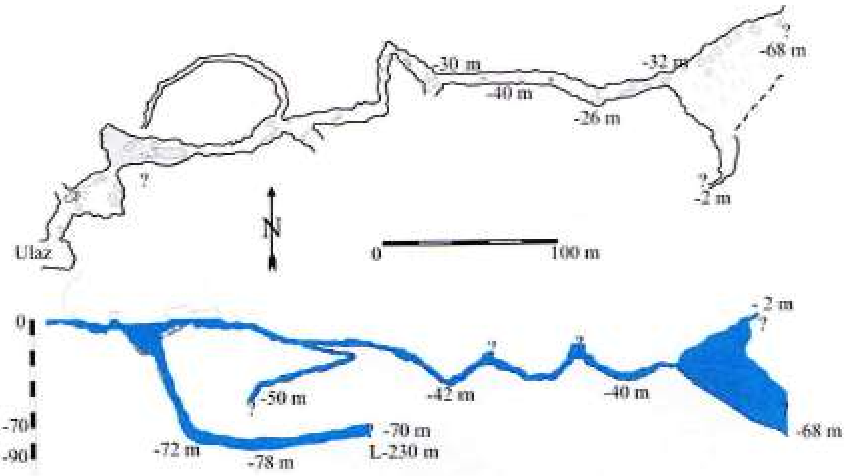


Figure 10: Speleological sketch of the cave channel "Vrelo Buna"

4 km south from "Vrelo Buna" (*Figure 11*) is the source of "Bunica". The source "Bunice" is located at the elevation 63 m.n.m. The springs are descending-overflow type, and it rises at the contact of permeable cretaceous limestone and impermeable sediments of the Eocene flych.

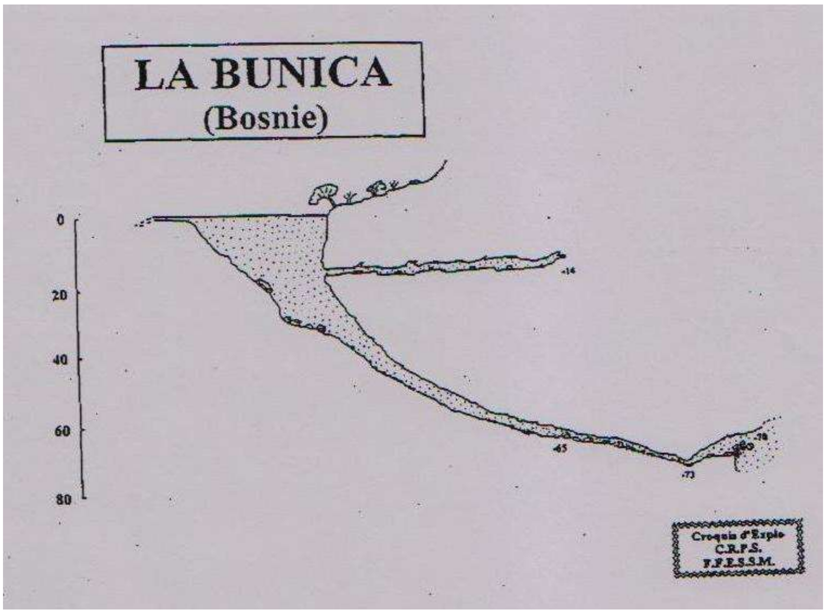


Figure 11: Speleological sketch of the cave channel "Bunica"

The flow rates of groundwater in the "Bunice" aquifer were determined by tracer testing, by the diving of the "Biograd" sink in the southwestern edge of Nevesinjsko polje. The subterranean link of "Biograd" with the spring "Bunica" represents one of the most direct underground links in the Dinaric karst with the underground flow rate of 33.67 cm / s.

The delineation of the catchment areas of the "Vrelo Buna" and the source "Bunica" is very complicated. The hydrogeological investigations so far have shown that there is no mutual hydrographic connection between the "Vrelo Buna" and the "Bunica" source. However, the geomorphologic characteristics, geological and hydrogeological characteristics of the terrain, the type of aquifers, the conditions of feeding and drainage, the water chemistry, the type of source and their quantitative and qualitative regime indicate that the ***springs of "Vrelo Buna" and "Bunica" have a very similar genesis***. The results of tracer groundwater testing that do not show their interconnection can be caused by complex hydraulic and filtration conditions and pressures of groundwater in the aquifer. The issue of the demarcation of the "Vrelo Buna" and "Bunica" catchment is of great importance and it is possible to separate out the isotopic signal of the precipitation in the catchment area and water these sources.

4.6 Hydrodynamic characteristics of the springs

The “Vrelo Buna” spring is characterized by large oscillations of flow and extremely high maximum yield. The basic characteristics of the hydrological regime of “Vrelo Buna” at the watermeter Blagaj station are:

- Average flow, Qsr = 23.70 m^3/s
- Minimum flow, Qmin = 2,95 m^3/s
- Maximum flow, Qmax = 380 m^3/s

The line of inclination of the tarisman curve with regression conditions is extremely steep, which results from the nature of feeding through concentrated flows (sinks), and depending on the precipitation regime.

Based on the discharge curve, the "Vrelo Buna" emission coefficient has a value α = 0.01056 of the tarisman equation has the form

$$Q_t = 20 \times e^{-0{,}01056\, t}$$

The volume of accumulated water in the recession period is Vo = 163.64 x 10^6 m^3 while the residual reserves are Vt = 85.91 x 106 m^3 (I. Slišković, 1983, p. 315).

The retardation capabilities of the aquifers that emptied on the “Vrelo Buna” are very good.

Basic characteristics of hydrological regime of “Bunica” on the water station Malo polje:

- Average flow, Qsr = 20.25 m^3/s
- Minimum flow, Qmin = 0,72 m^3/s
- Maximum flow, Qmax = 207 m^3/s

The general equilibrium equation for “Vrelo Buna” and “Bunica” has the form:

$$P = Q + R + E$$
$$1937{,}10 \times 10^6 = (\,1027 + 2341{,}10 + 569\,) \times 10^6$$
$$100\ \% = 53\ \% + 17\ \% + 30\ \%$$

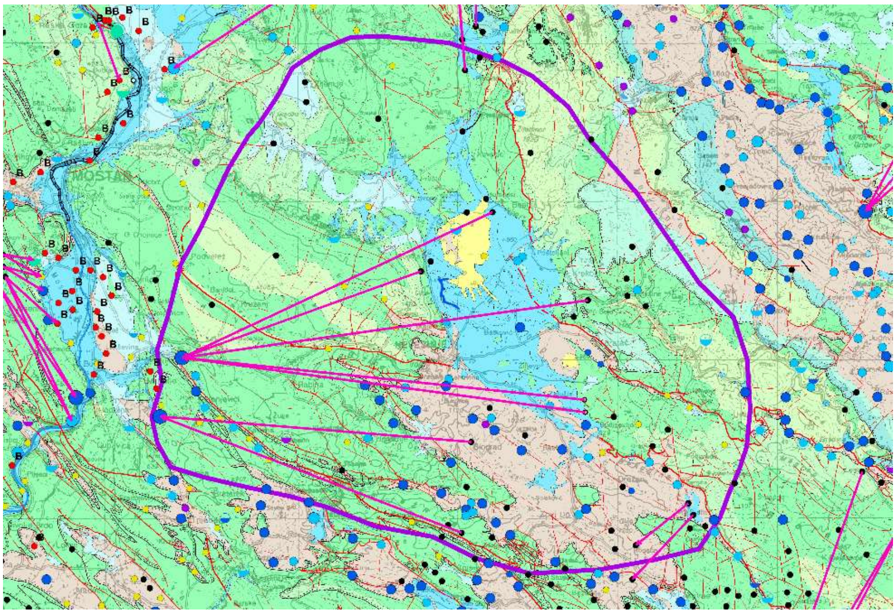
4.7 Data available for the project

1. Vrelo Buna spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	5 year	01/2015-12/2019
Electrical conductivity	4 times a year	5 year	01/2015-12/2019
Temperature	4 times a year	5 year	01/2015-12/2019
pH		5 year	01/2015-12/2019
Dissolved oxygen O_2	4 times a year	5 year	01/2015-12/2019
Suspended matter	4 times a year	5 year	01/2015-12/2019

Major anions/cations	4 times a year	5 year	01/2015-12/2019
NH_4	4 times a year	5 year	01/2015-12/2019

2. Bunica spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	5 year	01/2015-12/2019
Electrical conductivity	4 times a year	5 year	01/2015-12/2019
Temperature	4 times a year	5 year	01/2015-12/2019
pH		5 year	01/2015-12/2019
Dissolved oxygen O_2	4 times a year	5 year	01/2015-12/2019
Suspended matter	4 times a year	5 year	01/2015-12/2019
Major anions/cations	4 times a year	5 year	01/2015-12/2019
NH_4	4 times a year	5 year	01/2015-12/2019

4.8 Summary

Pilot name	**VRELO BUNE**		
Country	Bosnia and Herzegovina	EU-region	Mountain areas
Area (km^2)	1100	Lithology	Limestone & dolomite
Short description: „Vrelo Buna“ is one of the most famous and largest springs in the Dinarides. It is formed at the contact of Cretaceous limestone and eocene flysch, at an altitude of 64 m. The basin area is estimated at more than 1100 km^2. The spring has concentrated outflow from the cavity channel, and according to the latest research, the ascending mechanism			
Monitored objects	Springs		
Monitored data	Discharge, temperature, EC, chemistry, major anions/cations		
Contact person	Ferid Skopljak (ferid.skopljak@fzzg.gov.ba)		

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5 CZECH REPUBLIC: THE BÝČÍ SKÁLA (BULL ROCK) DISCHARGE AREA

5.1 Overview

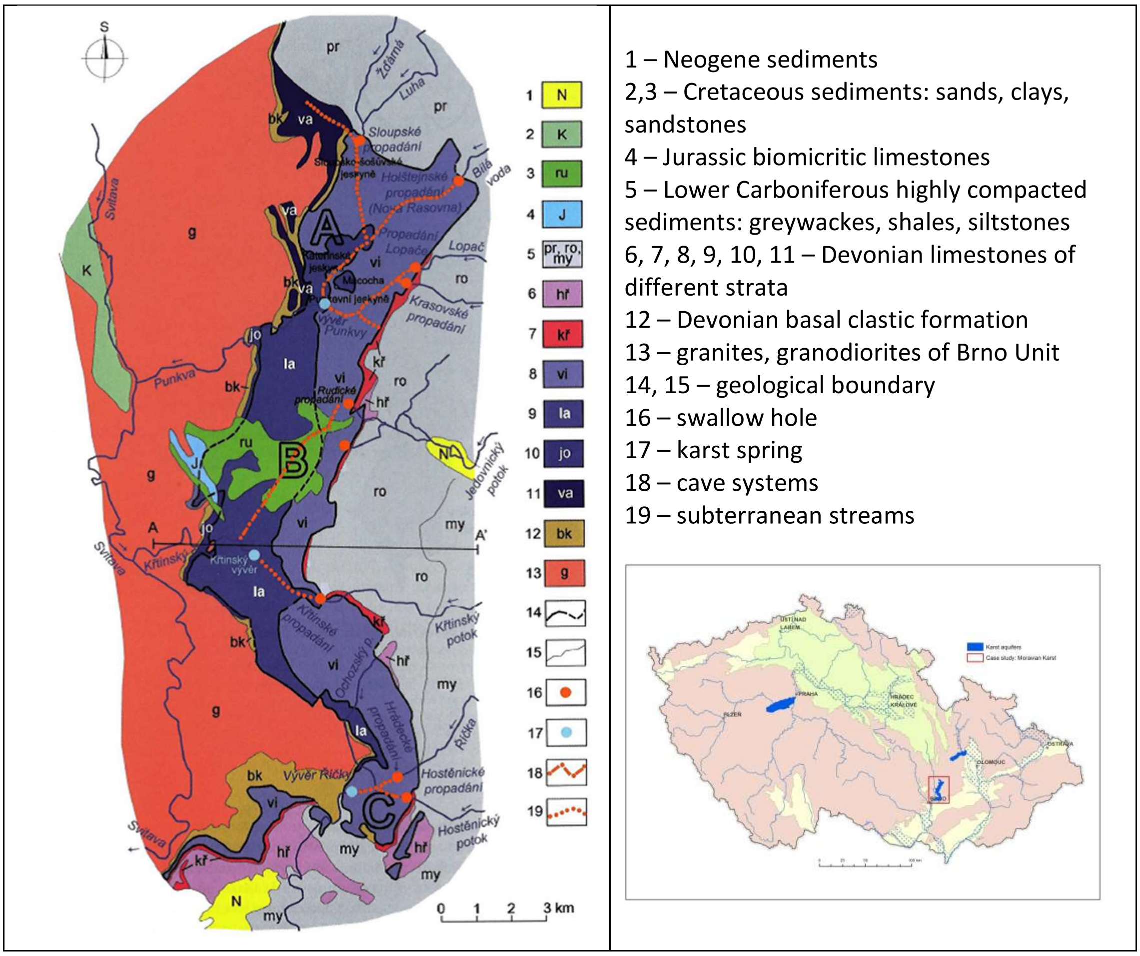
The study area of Býčí skála (Bull Rock) consists of a group of springs and karst springs forming the discharge of the Jedovnický sinking stream and Křtinský sinking stream catchment. The area is situated in the central part of Moravian Karst, the best known karst area of the Czech Republic with highly developed karst features. Býčí skála (Bull Rock) cave itself is a large cave system connected via siphons to the cave system of Rudický ponor, the ponor cave system of Jedovnický stream. The total length of the system is ca. 15 kms. Jedovnický sinking stream and Křtinský sinking stream are allochthonous streams coming to the karst area from the upland built by highly compacted Lower Carboniferous sediments. After outflow in the Býčí skála group of springs, they flow to the Svitava river representing the regional drainage base in the deep valley built by igneous rocks. The group of springs near the Býčí skála consists of several springs and classical karst springs. The Olomučanský springs, which belong to this group of springs, are used for water supply of the Adamov town nearby.

The Býčí skála cave is frequently called "the most memorable cave of the Moravian Karst", mostly on the account of its prehistory. The entrance part of the cave is the site of the famous "Hallstatt burial" containing the bronze statue of the bull, which was discovered by Jindřich Wankel in 1872.

5.2 Geology

The Moravian Karst is formed by Middle to Upper Devonian limestones, which are mostly light to dark grey, with white calcite crevice accretions. The block-structured belt of these limestones is approximately 30 km long, 4 km wide and up to 2 km thick. According to the stratigraphy, there are five types of limestones and the thickness of the series of strata is 500 to 1000 m. On the western side the limestones transgressively overlap the granitoids of the Bmo igneous massif, while on the eastern side they are in turn covered with Lower Carboniferous sediments. In some places, the relics of the denudated Jurassic and Cretaceous strata overlying them can be found and these sediments also form gravel pipes in some deep depressions. During the Neogene the Moravian Karst overflowed, and the rest of marine clays are still to be found in several places. The Quaternary Period is represented by different types of loams and debris and fluvial graves, sands and clays. The geological scheme of Moravian Karst and its surroundings is shown in *Figure 12*.

The karstification of the Devonian limestone complex is irregular, from small fissures with sinter crust to big caverns several metres wide and deep linear karstification zones. The cave system is developed in different vertical levels.



1 – Neogene sediments
2,3 – Cretaceous sediments: sands, clays, sandstones
4 – Jurassic biomicritic limestones
5 – Lower Carboniferous highly compacted sediments: greywackes, shales, siltstones
6, 7, 8, 9, 10, 11 – Devonian limestones of different strata
12 – Devonian basal clastic formation
13 – granites, granodiorites of Brno Unit
14, 15 – geological boundary
16 – swallow hole
17 – karst spring
18 – cave systems
19 – subterranean streams

Figure 12: Geological scheme of Moravian karst and its surroundings (Krásný 2012).

5.3 Geomorphology

The Moravian Karst is situated to the area of Drahanská Upland, the elevation parts of which do not excced 600 a.s.l. The landscape character of Moravian Karst is formed by plateaus with many sinkholes separated by deep canyon grooves. Most of the streams coming from the non-karstified part of the Drahanská Upland sink into the cave systems where the limestone area begins. The sinking streams created various cave labyrinths with many types of speleothems. Moravian Karst is divided into three parts beloning to different river catchments. The northern part of Maravian Karst is drained by the Punkva River and its tributaries. The Amatérská cave, the largest cave system in Czech republic, is to be found in the northern part of Moravian Karst with almost 35 km of tunnels and corridors. The southern part of Moravian Karst is a part of the Říčky sinking stream catchment with the Ochozská cave system.

The area of interest is situated to the central part of Moravian Karst to the Jedovnický and Křtinský stream catchment and is shown in *Figure 13*. The cave system Rudický ponor – Býčí skála cave formed by the Jedovnický sinking stream is the second longest in the Czech Republic, the overall length of the system is 12 km (see *Figure 13*). The Jedovnický stream sinks to a depth of 86m by several waterfalls, it has formed high canyons, huge halls as well as places very difficult to pass through. The Býčí Skála Cave and its suroundings is the discharge area of this cave system. The subterranean part of Křtinský stream and the cave system formed by it is mostly unexplored up to now.

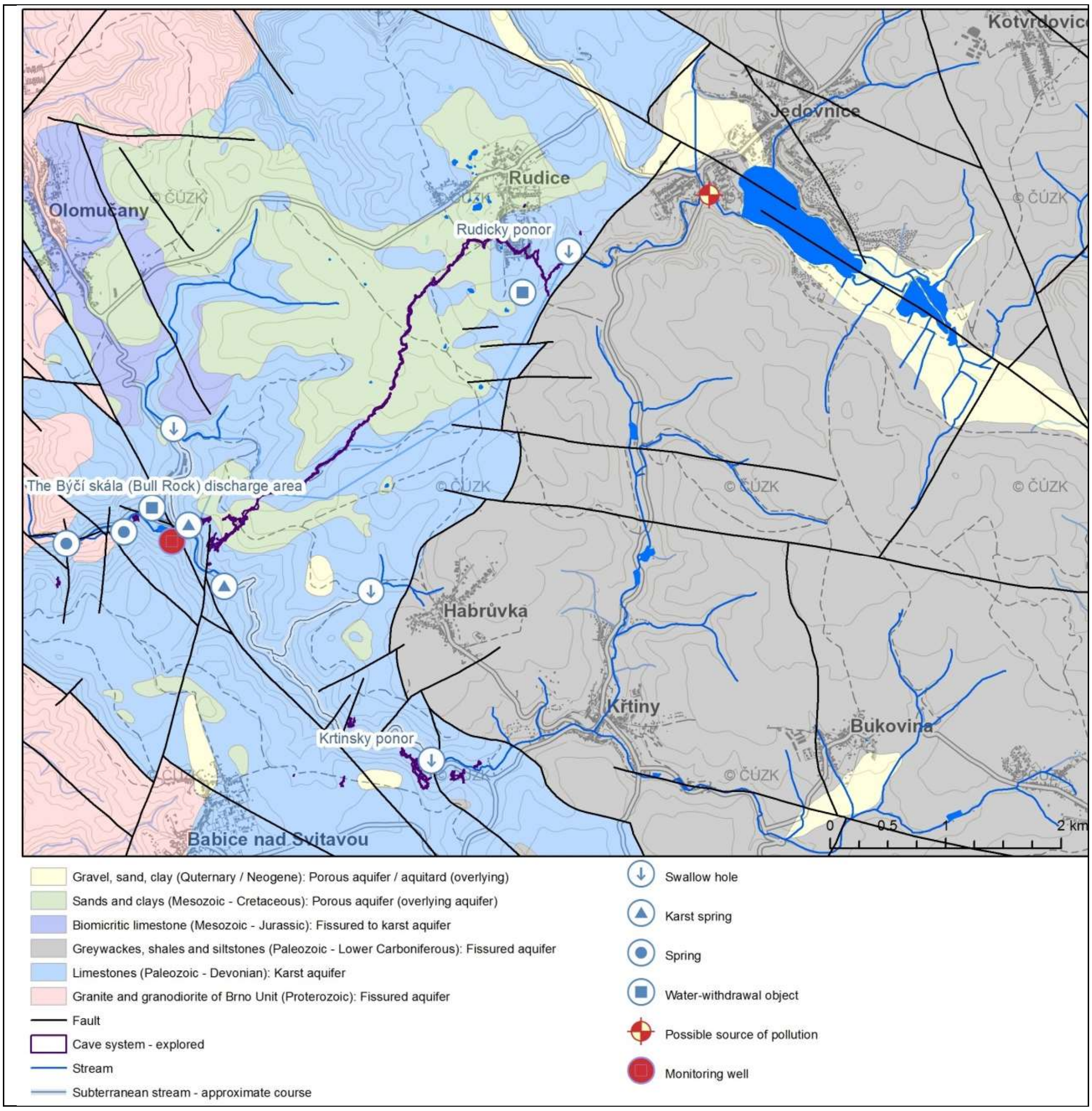


Figure 13: Scheme of Jedovnický and Křtinský stream catchment and its discharge area at Býčí skála

5.4 Climate

The climate character of the area fluctuates from humid continental to temperate oceanic. The average annual temperature is ca. 8, 5 °C. The temperature difference between summer and winter is relatively high, in January the average temperature is -2, 5 °C and in July 18, 5 °C. The area receives around 550 mm annual precipitation, most of it during summer period. Sporadic rainfall is relatively constant throughout the year but concentrated heavy rainfall is more frequent in the months of May to August.

5.5 Hydrogeology

Moravian Karst is an open transit karst-fissured hydrogeological structure according to Kullman (1990). The structure is recharged not only with infiltration of rainfall and with surface water inflow, but also with lateral drainage from non-karstified surroundings. Due to the geological position between fissured aquifers and morphological character with low-level drainage base, Moravian Karst acts as a water-trap. Hydrogeological structure of Moravian Karst is drained by springs and stream, part of the water recharges deeper circulation systems within carbonate rocks and is drained into clastic sediments of Carpathian Foredeep. The existence of grounwater communication between karst hydrogeological sructure ond its non-karstified surroundings is serious obstruction for the evaluation of natural groundwater resources.

The study locality itself covers the Jedovnický nd Křtinský stream cathcments. These sinking streams flow through the structure in open channels and feed the main karst springs in the drainage area near Býčí skála. Besides this concentrated flow in conduits there is a diffuse flow in fissured matrix, which in fact form more than 99,9 % of karst aquifer. Some of the springs in the drainage area are fed with groundwater from the fissured matrix, e. g. the Olomučanský spring (water withdrawal object), which is not connected to any sinking stream.

5.6 Hydrodynamic characteristics of the springs (and river)

The flow rates measured in the karst springs at Býčí skála vary widely in dependence on climatic conditions. High flow rates exceeding 1 700 l/s were registered in 2010 (Kůrková 2011) during extremely rainy period. During dry periods, the flow rates do not exceed 70 l/s, some of the springs are even intermittent. The flow rate of the Křtinský karst spring reaches 250 l/s during rainy periods and does not exceed first tens of l/s during dry periods.

The yield of the water withdrawal object, Olomučansky spring is more stable, which may point to the contribution of deeper groundwater circulation.

5.7 Data available for the project

1. Monitoring well VB9807			
Data type	Time step	Monitoring period	Time period
Groundwater level	continuous	> 10 years	1988–present
Major anions/cations	half-yearly	> 10 years	1988–present
Pesticides	half-yearly	5–10 years	2014–present
Nutrients	half-yearly	> 10 years	1988–present

2. Olomučanský spring			
Data type	Time step	Monitoring period	Time period
Major anions/cations	yearly	> 10 years	1980–present
Nutrients	yearly	> 10 years	1980–present
Discharge	weekly	> 10 years	1980–present

3. Josefov, Křtiny, Jedovnice river gauge station			
Data type	Time step	Monitoring period	Time period
Flow-rate	daily	> 10 years	1975–2000
Flow-rate	continuous	> 10 years	2000–present

4. Other springs			
Data type	Time step	Monitoring period	Time period
Chemistry	occasional data		
Flow-rate	occasional data		
Stabile isotopes	occasional data		

In addition, data from trace tests are available. Monitoring objects are shown Figure 16

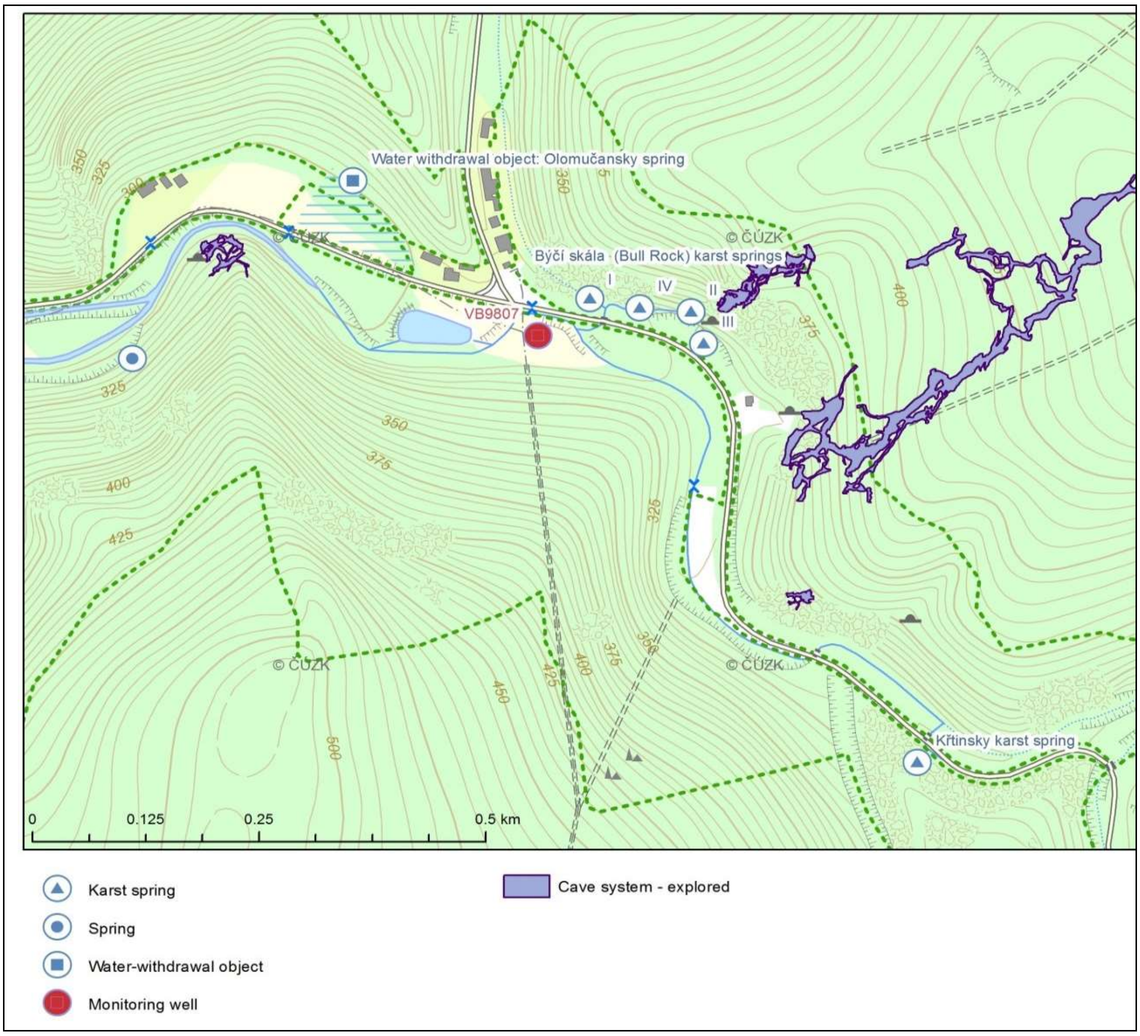
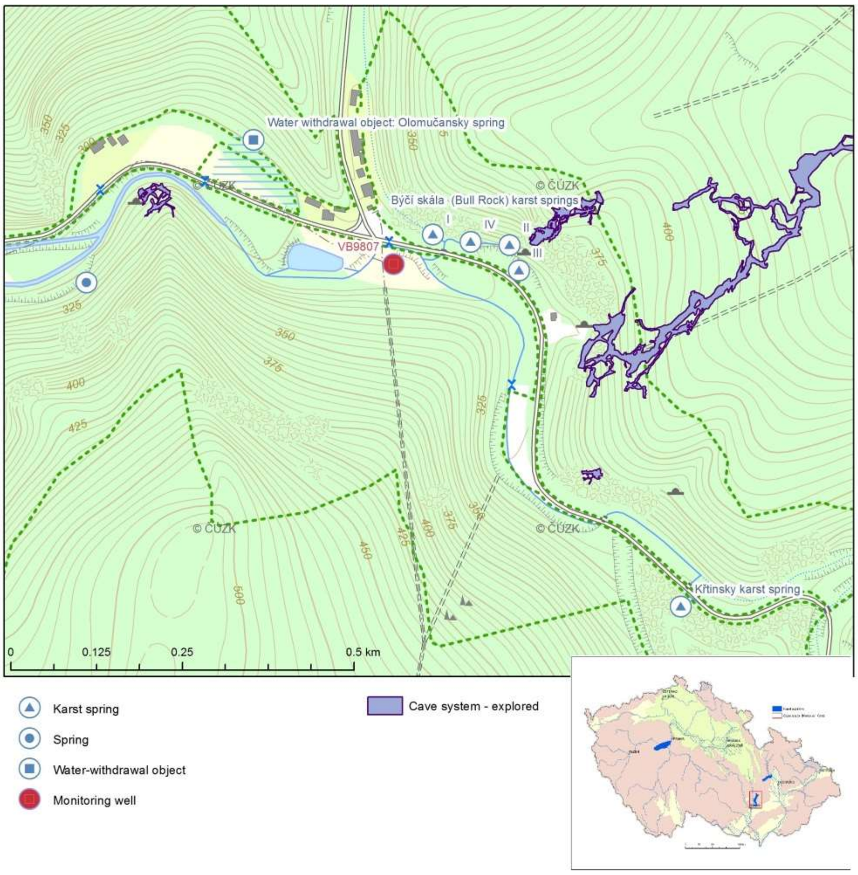


Figure 14: Detailed scheme of the Býčí skála discharge area.

5.8 Summary

Pilot name	**The Býčí skála (Bull Rock) Springs – discharge area of the Jedovnický and Křtinský sinking stream catchment**		
Country	Czech Republic	EU-region	Central Europe
Area (km²)	65	Lithology	Limestone
Short description: Býčí skála (Bull Rock) group of springs is the discharge area of the karst hydrogeological structure in the catchment of the Jedovnicky and Krtinsky sinking streams. Flow rates of the main springs vary widely due to climatic conditions. One of this group of springs, Olomučansky spring, is used for water supply of the Adamov town nearby.			
Monitored objects	Well (one), spring (two), river gauge station (three)		
Monitored data	Groundwater level, discharge, flow rates, temperature, EC, chemistry, (isotopes, fluorescence – occasionally)		
Contact person	Eva Krystofova (eva.krystofova@geology.cz)		

5.9 References

- Krásný, J. (2012): Podzemní vody České republiky. (Groundwater in the Czech Republic.) – Česká geologická služba. Praha.
- Kullman, E. (1990): Krasovo-puklinové vody. (Karst-fissured waters). – SGUDS. Bratislava.
- Kůrková, I. (2011): Charakter proudění a šíření hydraulické odezvy ve vybraných jeskyních Moravského krasu. (Flow pattern and hydraulic response propagation in selected caves of Maravian karst – diploma thesis.) – Univerzita Karlova. Praha.

6 IRELAND: KILLEGLAN SPRINGS

6.1 Overview

Killeglan spring is actually made up of two springs, the largest of which, Tobermore Spring, is used as a drinking water source for the surrounding region. There are three boreholes located in the spring compound, but it is unclear how much water, if any, is abstracted from the boreholes.

The Killeglan spring and boreholes are situated in the low-lying central plain of Ireland (*Figure 15*). Almost half of the Republic of Ireland is underlain by limestone, over 80% of which lies at an altitude of less than 100 m (*Figure 16*). However, the lowlands are not obviously karstic. Glacial sediments, principally till and peat deposits, overlie the limestones in varying thicknesses. This mantle of Quaternary deposits allows a surface drainage system to exist in places. The Irish karstic lowlands are often characterized by high water levels and severe flooding in winter (Hickey, 2010). Turloughs (seasonal karstic lakes) are abundant in the area. Lowland karsts are probably the most developed and complex karst regions of Ireland, comprising a mixture of re-activated, pre-glacial and inter-glacial karst and Holocene karst.

Much of surface drainage system has been altered by arterial drainage works. Prior to the arterial drainage works, most of the rivers in the western part of this region sank underground. Further east, where Quaternary deposits are thicker, and the limestones are less pure, the surface drainage pattern was largely the same as at present. As with the limestone east of the region (east of the River Shannon), thick subsoils mask much of the bedrock topography, with only isolated exposures of bedrock protruding above the undulating or flat terrain (Drew, 2018). A feature of the study area is the existence of tracts of land (mini-plateaux) with areas of up to tens of square kilometres elevated 20 - 40 m above the surrounding lowland, with no integrated surface water channels and draining to small-medium springs around the periphery. In other areas, the karstic lowlands are also littered with small to medium sized karst springs, often with no obvious catchment area (Hickey, 2008; Drew, 2008; Drew, 2018). The Killeglan spring is one such spring. Exceedances of trihalomethanes and turbidity standards and detections of Cryptosporidium and Clostridium perfringens in this supply have been notified to the Environmental Protection Agency (EPA) in the past.

The catchment area to the spring has been delineated and encompasses an area of approximately 40 km^2. The area is sparsely populated with agricultural activity dominating and most of the land used for grassland and grazing. The nearest town is Ballinasloe, located 10 km to the south and outside the catchment. Athlone is located 15 km to the east and also outside of the catchment area. A high density of karst landforms, such as turloughs, intermittent streams and small autogenic sinking streams are mapped in the catchment. A number of houses and farms are present near the spring, some of which are within 500 metres of the source.

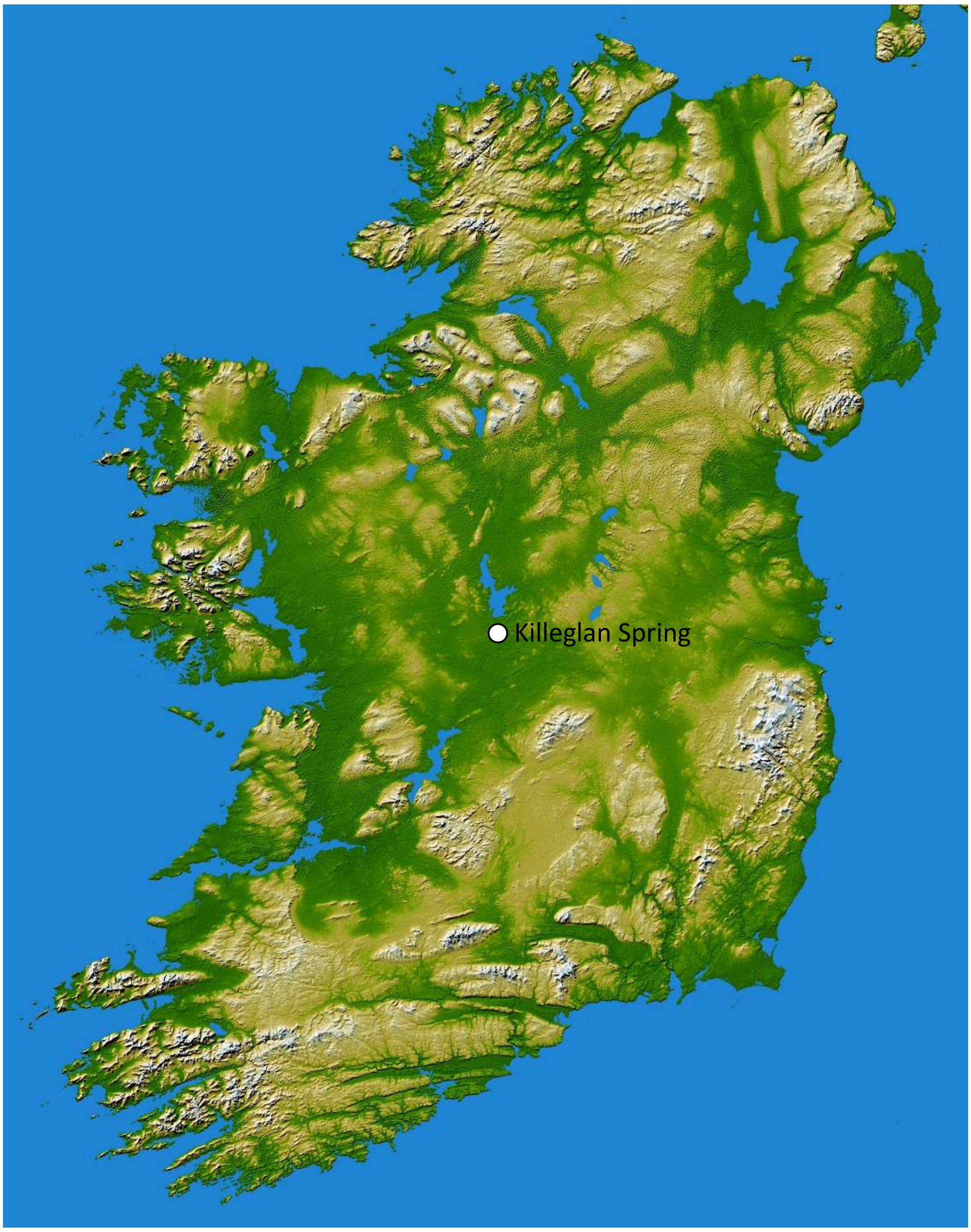


Figure 15: *The topographical setting for Killeglan spring*

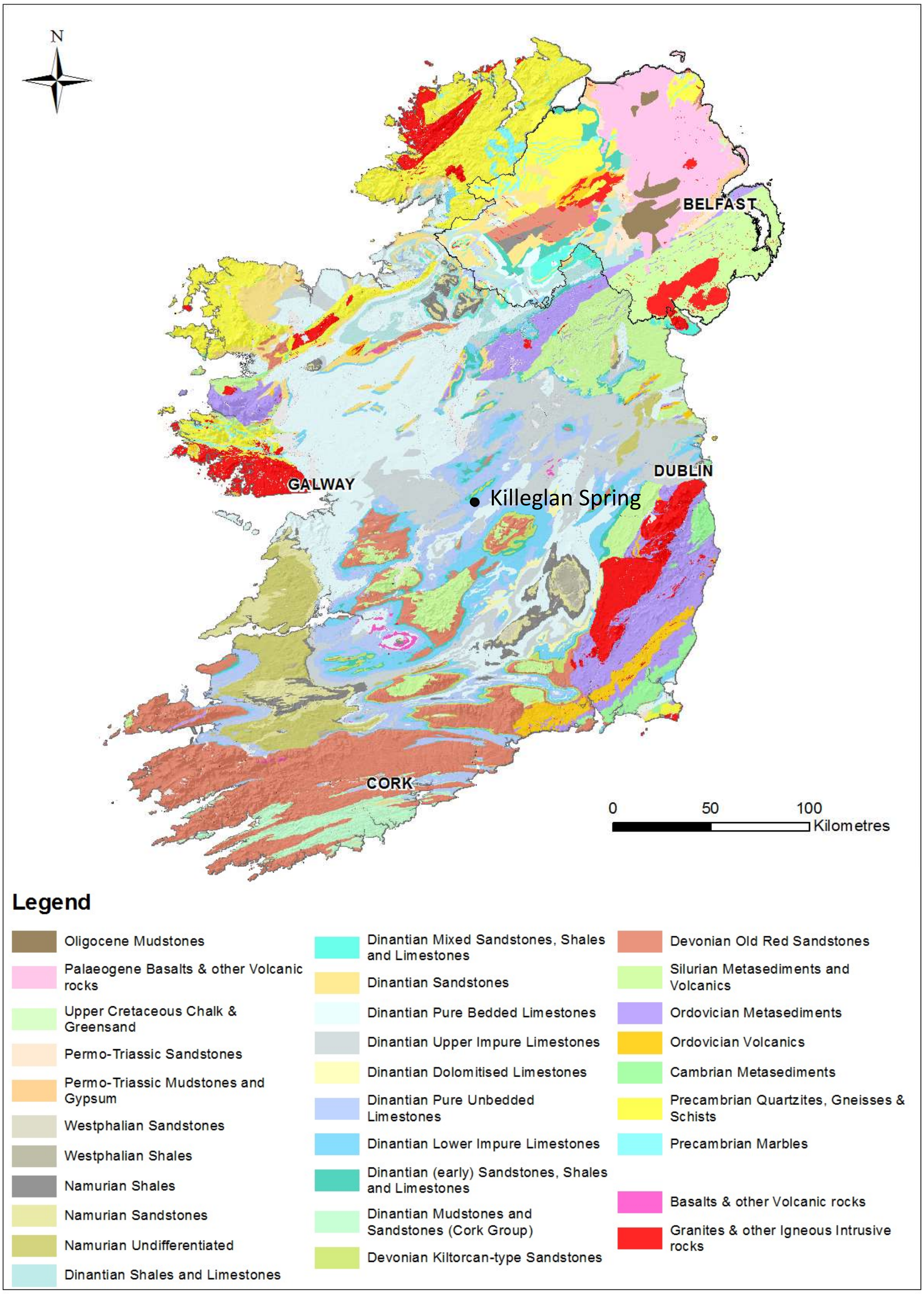


Figure 16: All Ireland Rock Unit Group Map (data from GSI) showing the location of Killeglan Spring

6.2 Geology

6.2.1 *Bedrock Geology*

The majority of the midlands is underlain by limestone bedrock. In fact, the spring is located in one of the largest continuous areas of limestone in Northwest Europe (almost 20,000 km^2 in area) (*Figure 16*). The majority of the pilot area is underlain by Undifferentiated Visean Limestone (*Figure 17*). These limestones are undifferentiated due to poor exposure but are generally composed of pure, medium- to coarse-grained bedded limestones. A number of small outcrops of the Visean Limestone are noted along the path of the intermittent, seasonal stream, within the catchment. To the south of the Visean Limestone is a thin band of Waulsortian Limestone. The Waulsortian Limestone is a clean, pale grey massive limestone (Morris et al., 2003). The older Ballysteen Limestone is exposed further south and east but outside the catchment area. This limestone is described as a dark grey muddy limestone interbedded with calcareous shales.

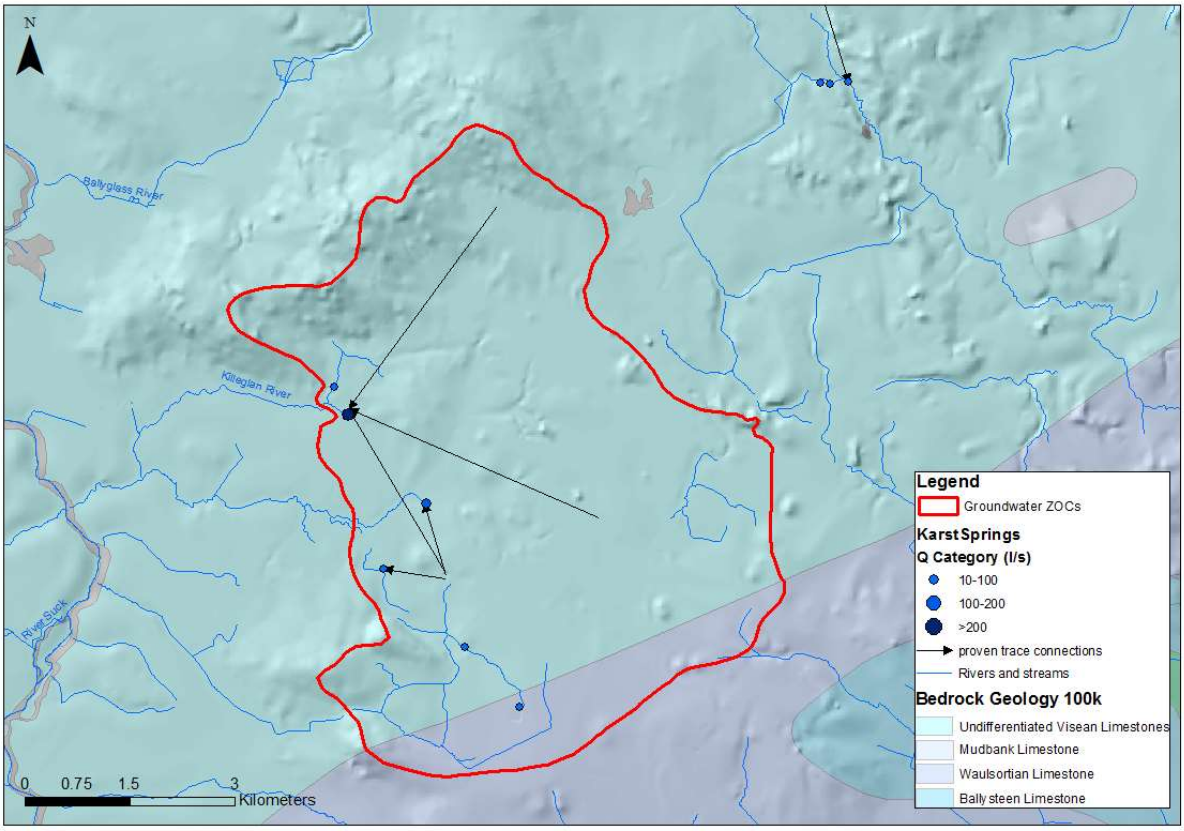


Figure 17: *The bedrock geology of the Killeglan spring catchment and surrounding area*

6.2.2 *Quaternary Geology*

The unconsolidated material (subsoil) overlying the bedrock comprises a mixture of coarse and fine-grained materials, namely peat, alluvium, sand/gravels, and tills (*Figure 18*). Till is the dominant subsoil type in the area and is an unsorted mixture of coarse and fine materials laid down by ice. The gravel-sized fragments ranging up to 10 cm in size are angular to sub-rounded and are composed of limestone. The matrix is primarily silty SAND (BS 5930) with frequent gravels and clay (Lee & Kelly, 2003). It is classified as being moderately permeable. Peat is located in the low-lying boggy regions of the area, mostly in the southern part. Extensive glaciofluvial sand/gravel deposits are present east and north-east of the springs. A large proportion of the sand/gravel forms a characteristically random, hummocky topography. However long, sinuous, braided ridges of sand/gravel (eskers) have also been deposited (Lee & Kelly, 2003). Lacustrine deposits and lake marl are found around the larger turloughs in the catchment area. Alluvium is deposited in the larger river valleys, such as the Suck River, to the west, and other smaller localised areas within the catchment.

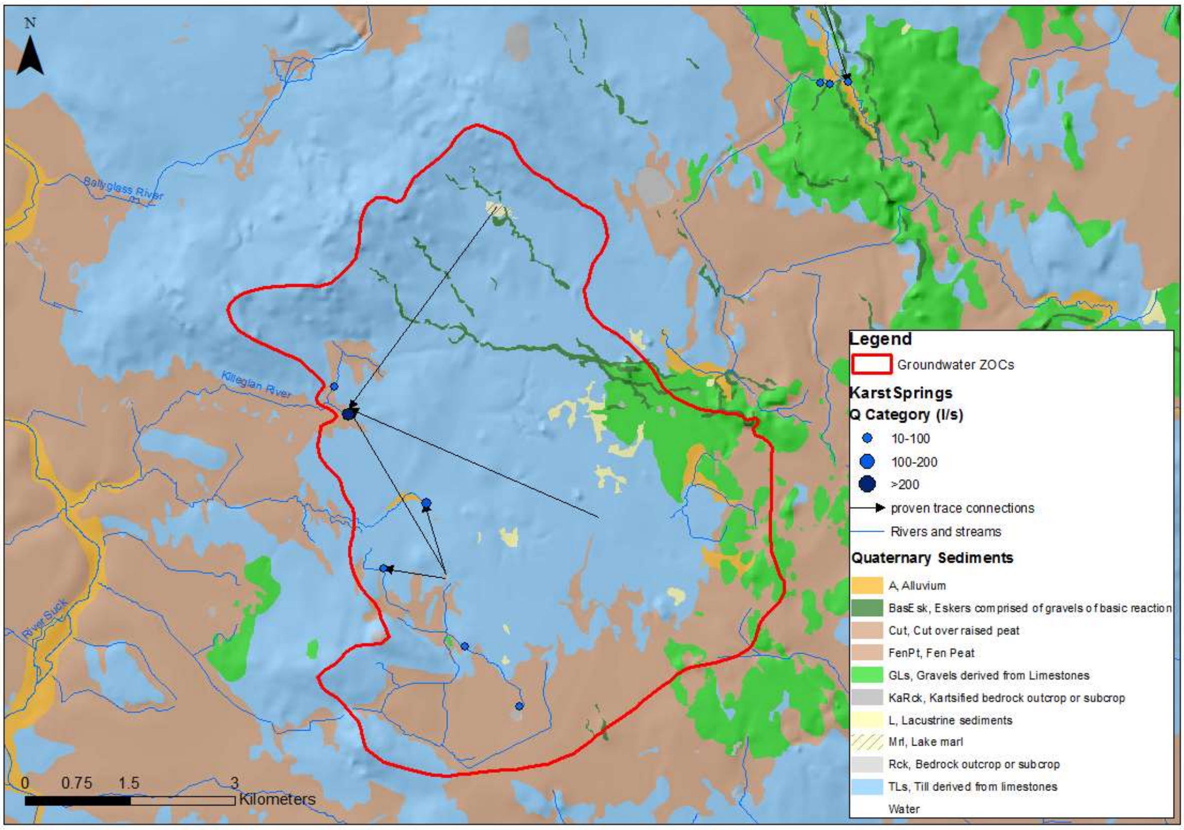


Figure 18: *The Quaternary Geology of the Killeglan spring catchment and the surrounding area*

6.2.3 Depth to Bedrock

Broad variations in depth to bedrock have been interpreted across the area by using information from the GSI databases, field mapping and air photo interpretation. Data from the drilling programmes indicate that the depth to rock ranges from 2 m to 33 m. In general, the low-lying areas around the spring and towards the central part of the catchment are closer to bedrock. Higher parts of the catchment have greater depths to bedrock.

6.3 Geomorphology

As previously stated, the springs are located in a low-lying region in Ireland, with very little land higher than 100 m above sea level (asl). The spring emerges at 50 m asl. The area immediately around the springs is flat to undulating (*Figure 15*). However, there is a slight rise to the east with the land to the east of the springs elevated some 10 m above, with an average height of about 60 m asl. There is also a small elevated ridge to the north of the springs, rising to maximum of 119 m asl.

There is a large river, the River Suck, located 4 km west of the springs, which the springs overflow into (*Figure 18*). This river flows south, eventually joining the River Shannon at Shannonbridge. This river drains the majority of the area shown in the figures. To the east of the springs lies the River Shannon, Ireland's largest river. This river flows south through a series of large lakes and eventually flows out to sea at Limerick via the Shannon Estuary. One of these lakes is Lough Ree, located some 15 km northeast of the springs.

The surface water regime in the catchment is closely interconnected with the groundwater regime. There are several springs, swallow holes and numerous enclosed depressions that are linked to the main surface water bodies in the area (*Figure 19*). Many streams sink a short distance after they rise. An intermittent, seasonal stream is located to the east of the Tobermore spring. Karst landforms are abundant in the catchment, and beyond, with many areas draining into turloughs and subsequently entering the groundwater system in swallow holes as and when the turlough empty.

There are a number of glacial geomorphological features such as eskers ridges, hummocky sand and gravel deposits and ribbed moraines.

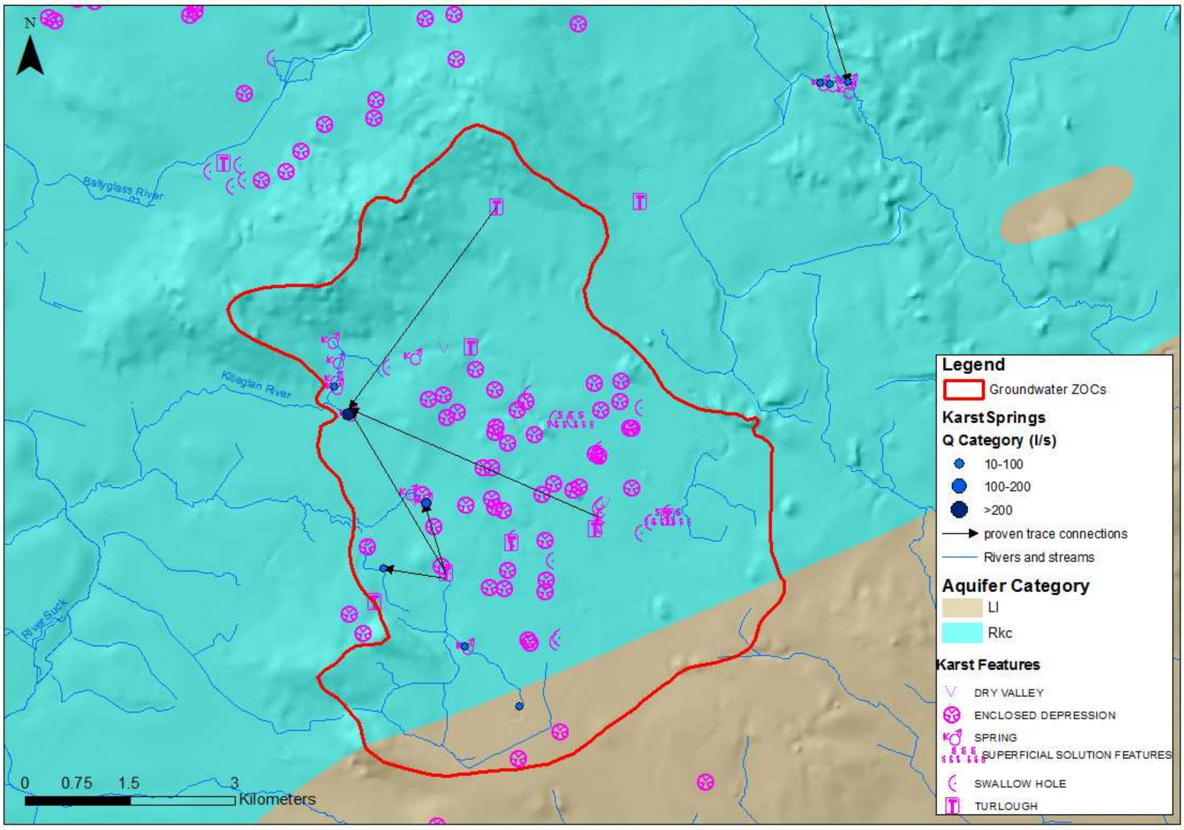


Figure 19: *The karst landforms, surface drainage features and aquifer category of the Killeglan spring catchment and the surrounding area*

6.4 Climate

Ireland has a temperate maritime climate, which is greatly influenced by the Atlantic Ocean. The climate of Ireland has abundant rainfall and lacks temperature extremes. The mean annual air temperature of Ireland is approximately 10°C, but with an average of 10°C difference between January and July, the weather is more consistent than in other areas at a similar latitude. Average annual rainfall ranges from 750 mm to >3000 mm. The eastern part of the country receives an annual average of 750 to 1,000 mm, while the western part of the Ireland receives an annual average of 1,000 to 1,300 mm of rainfall. Mountainous areas receive greater than 3,000 mm per annum. The average rainfall in the study area is 1,040 mm/yr (Met Eireann 30 year averages, 1981-2010). Major snowstorms are rare in Ireland, with most winters remaining snow free.

6.5 Hydrogeology

Killeglan spring discharge is made up of a cluster of two springs (*Figure 19*). The main spring is called 'Tobermore' as it used as a drinking water supply. There is a smaller spring to the north of this. The overflow from both of these springs combines to form the Killeglan River, which is used for monitoring by the EPA (and used to calculate discharge values for this report). A third smaller spring, called Bellaneeny Spring outflows through Bellaneeny stream, 1.7 km to the south of Tobermore. There are more springs further south of this again. All these springs discharge into the River Suck 4 km to the west.

6.5.1 Surface hydrology

There are four main stream networks in the vicinity of Tobermore Spring. These are as follows:

1. Just north of Taghmaconnell, a stream rises in the townland of Bellaneeny. This stream flows west for approximately 4 km, to join the Killeglan River, which then discharges in the River Suck.
2. A stream network exists to the south of Taghmaconnell, in the townlands of Knock and Sraduff. These streams flow to a turlough in the townland of Glennanea. This turlough appears to take all the flow from the stream network. Another section of stream rises east of this network and then disappears after flowing approximately 1 km to the north-east.
3. An intermittent, seasonal stream is located to the east of the Tobermore Spring. This stream rises in the townland of Carrowduff and Garbally, and travels first north and then east. During wet weather the upper parts of the stream are flowing. Groundwater from the Tobermore Spring and discharge area joins this channel to form the head of the Killeglan River.
4. A small stream network is located in the townland of Esker. This stream network is recorded as having permanent flow but has no apparent surface water outlet. It is therefore likely that this area of surface water feeds into the groundwater system (Lee and Kelly, 2003).

To summarise, the majority of the outflow from this area is via the Killeglan River, which includes the Tobermore Spring discharge. A second smaller outflow is through the stream at Bellaneeny, south of the springs.

6.5.2 *Groundwater Levels, Flow Directions and Gradients*

The water level at Tobermore Spring is at ground level and the entire flat, low lying area around the spring is saturated and marshy. Tobermore Spring is located in a discharge area that comprises at least three other springs. Other springs also occur along the intermittent, seasonal stream, near the Tobermore Spring. The occurrence of springs and saturated ground in low-lying areas generally indicate a shallow water table. Water level surveying indicates the general features of the water table, such as the level, direction, and gradient. The contours are widely spaced which suggests high permeability. The flow directions interpreted from the map indicate that groundwater flows toward the springs from the south-east, east, north-east and north. The groundwater gradient calculated from the water table map is 0.0015 (Lee and Kelly, 2003).

6.5.3 *Karst landforms*

A brief karst mapping programme undertaken in the Killeglan area identified a large number of features. As previously mentioned these included enclosed depressions (dolines), swallow holes, sinking streams, springs and turloughs (*Figure 19*). There is also a seasonal stream that runs through the catchment (marked by linear strip of extreme vulnerability in *Figure 20*). Most of the catchment drains into a swallow holes, seasonal or sinking streams or turloughs. So far there are 9 springs, 7 turloughs, 45 enclosed depressions and 26 swallow holes (as well as other karst landforms) mapped within the catchment. The mapping also highlights the density of dolines and swallow holes along the path of the intermittent seasonal stream.

6.5.4 *Dye tracing*

Tracer testing was undertaken at three different locations within the catchment indicating minimum groundwater velocities of between 70m/hr and 110 m/hr. It also clearly demonstrates the direct and rapid link between most of the catchment and the springs.

6.5.5 *Aquifer Category*

The Undifferentiated Visean Limestone, which underlies the majority of the area, is classified as a Regionally Important Karstic Aquifer, that is dominated by conduit flow (Rkc). Development potential of the clean Waulsortian Limestone is considered to be limited by its massive nature, and is therefore categorised as a Locally Important Aquifer, that is moderately productive in local zones (Ll) (*Figure 19*).

All of the Republic of Ireland's land surface is divided into nine aquifer categories, based on the hydrogeological characteristics and on the value of the groundwater resource. They are as follows:

Regionally Important (R) Aquifers

- Karstified bedrock (**Rk**)
- Fissured bedrock (**Rf**)
- Extensive sand & gravel (**Rg**)

Locally Important (L) Aquifers

- Karstified Bedrock (**Lk**)
- Sand & gravel (**Lg**)
- Bedrock which is Generally Moderately Productive (**Lm**)
- Bedrock which is Moderately Productive only in Local Zones (**Ll**)

Poor (P) Aquifers

- Bedrock which is Generally Unproductive except for Local Zones (**Pl**)
- Bedrock which is Generally Unproductive (**Pu**)

The Geological Survey's aquifer map distinguishes between limestones with and without a high degree of karstification. All limestone categories, depending on their permeability, storage capacity and areal extent, are categorised into Regionally Important (R); Locally Important (L); and Poor Aquifers (P). Regionally important limestone aquifers are subdivided into three categories. Where karstification is slight, the limestones are hydrogeologically similar to fissured rocks and are classed as Rf, although some karst features may occur. Aquifers in which karst features are more significant are classed as Rk. Within the range represented by Rk, two sub-types are distinguished, termed Rkc and Rkd (GSI, 2006; Hickey, 2018).

Rkc are those aquifers in which the degree of karstification limits the potential to develop groundwater resources. They have rapid flow velocities and a significant proportion of flow is concentrated in conduits focussed on large springs. Storage is low and locating areas of high permeability is difficult; therefore, groundwater development using bored wells can be problematical.

Rkd aquifers are those in which flow is more diffuse, storage is higher, there are many high yielding wells and the development of productive bored wells is less difficult. These areas may also have caves and large springs, but the springs flow regimes are less flashy than those in Rkc aquifers (GSI, 2008; Hickey, 2018).

6.5.6 Groundwater Vulnerability

All of the Republic of Ireland's land surface is divided into five groundwater vulnerability classes. The term 'vulnerability' is used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities (DELG/ EPA/GSI 1999). The vulnerability of groundwater depends on:

The travel time, attenuation capacity and quantity of contaminants are a function of the following natural geological and hydrogeological attributes of any area:

- the type and permeability of the subsoils that overlie the groundwater
- the thickness of the unsaturated zone through which the contaminant moves
- the recharge type – whether point or diffuse.

In other words, vulnerability is based on evaluating the relevant hydrogeological characteristics of the protecting geological layers along the pathway, and the possibility of bypassing these layers. In summary, the entire land surface is divided into four main vulnerability categories: **E**xtreme, **H**igh, **M**oderate and **L**ow, based on the geological and hydrogeological characteristics. A further sub-division of Extreme is for rock at or within 1 m of the land surface and around karst landforms (**X**). Further details of the hydrogeological basis for vulnerability assessment can be found in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999).

The catchment area for Killeglan spring has a range of groundwater vulnerabilities, as very little bedrock outcrops, and more than 95% of the catchment has depths to bedrock of greater than 5 m and over half has subsoil thicknesses of greater than 10 m (*Figure 20*). Extreme vulnerability is mapped along sinking streams, the entire stream up-gradient of swallow holes, at enclosed depressions and swallow holes and at any area of shallow bedrock. This accounts for only 3-4% of the catchment area. High vulnerability occurs at areas overlain by high permeability subsoils or shallower bedrock. This accounts for over 50% of the catchment area. Moderate vulnerability occurs at areas of thicker / less permeable subsoil, accounting for 33% of the catchment area, and low groundwater vulnerability occurs in areas overlain by greater than 10 m of low permeability subsoil. This accounts for approximately 8% of the catchment.

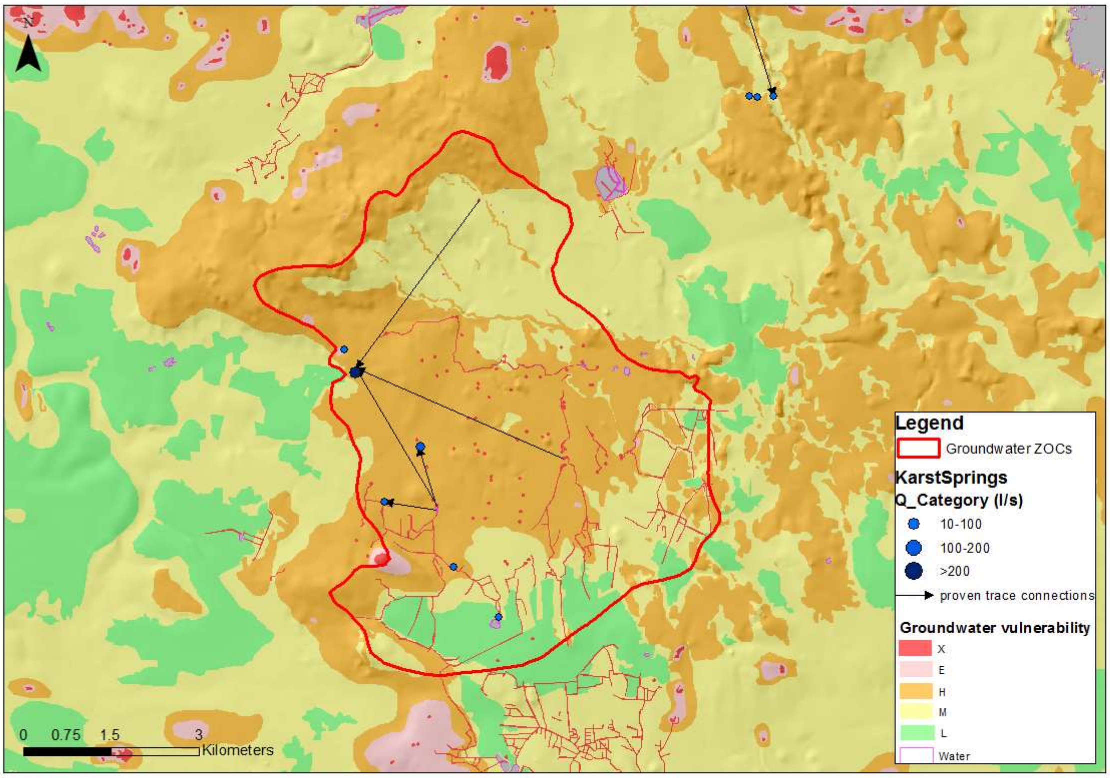


Figure 20: *Groundwater Vulnerability for the Killeglan catchment and surrounding area*

6.5.7 Groundwater Recharge

Groundwater recharge in the area is a combination of diffuse and point (through swallow holes, sinking streams and turloughs). A groundwater recharge map is available for the Republic of Ireland, which describes diffuse groundwater recharge. The main hydrogeological controls on groundwater recharge include the permeability and thickness of superficial deposits (mainly tills in Ireland), the presence of saturated soils, and the ability of the underlying aquifer to accept percolating waters. Combinations of these factors are assessed, and a 'recharge coefficient' is established for different hydrogeological scenarios. The groundwater recharge map is the result of the recharge coefficients multiplied by the effective rainfall. The recharge map is finally modified to take into account areas where the natural recharge capacity of the underlying aquifer is less than the estimated groundwater recharge potential (Hunter Williams et al., 2013). In karst areas additional point recharge can occur via swallow holes and sinking streams. This is not accounted for in the current groundwater recharge map.

Groundwater recharge in the Killeglan catchment area ranges from as little as 25 mm/yr, in areas of low permeability peat deposits, to over 560 mm/yr in areas where rock is at the surface, around influent karst landforms or areas of high permeability sand and gravel deposits (*Figure 21*). The majority of the catchment area has groundwater recharge rates of approximately 370 mm/yr. These values do not account for any inflow from sinking streams and influent karst landforms.

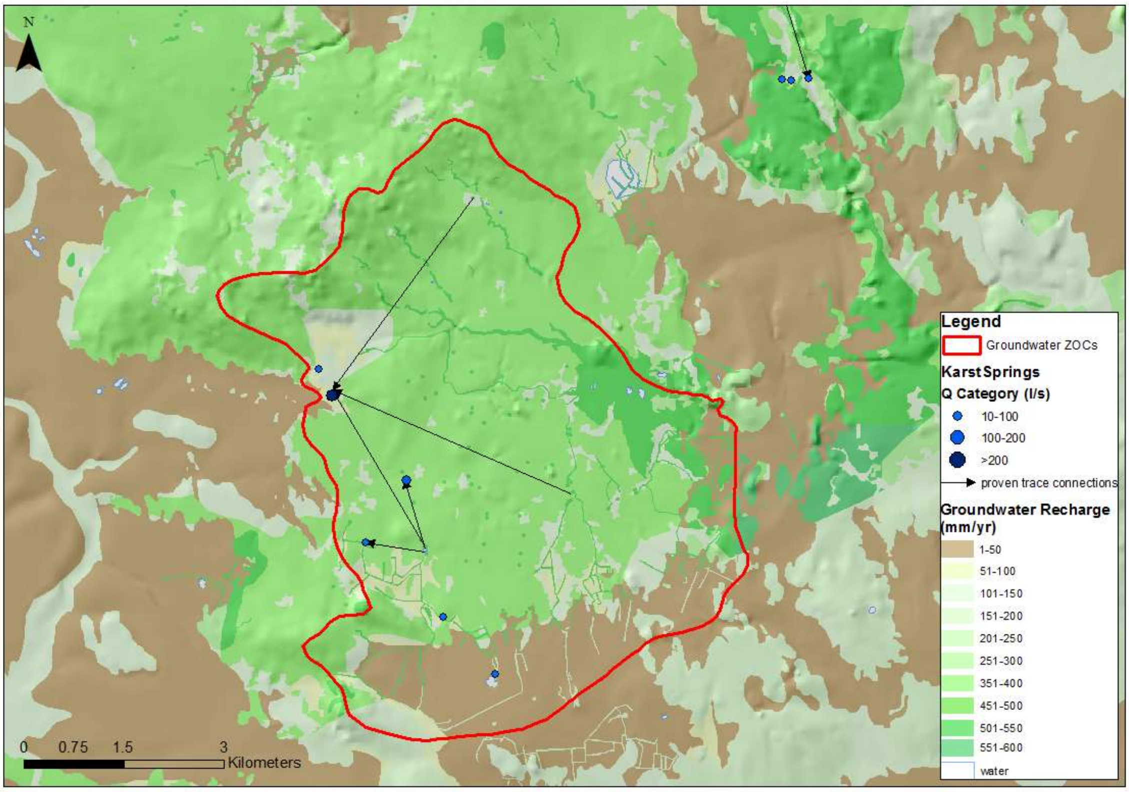


Figure 21: *Groundwater Recharge in the Killeglan catchment and surrounding area*

6.6 Hydrodynamic characteristics of the springs

Killeglan spring occurs in a discharge zone, made up of a cluster of medium sized karst springs. The overflow for Killeglan spring and some smaller springs to the north is monitored by the Environmental Protection Agency (EPA) as part of their long term Hydrometric monitoring network. The average discharge from the springs is approximately 0.5 m^3/s. The minimum discharge is 0.1 m^3/s, where the overflow dries up entirely and the maximum discharge is 2.4 m^3/s, though this is extremely rare (*Figure 22*). The amount abstracted by the drinking water source is unknown but is thought to be currently around 0.05 m^3/s. The supply is currently owned by Irish Water, Ireland's National water utility. They took over management of the spring in 2014 and upgraded the water treatment plant (*Figure 23*). Prior to this the customers on the scheme were on a 'boil water notice' since 2009 due to poor water quality. The drinking water abstraction in the past was approximately 0.1 m^3/s. It is not yet clear when the abstraction changed and the abstraction regime is not yet fully understood.

It is also not fully understood how much of the discharge comes from Tobermore Spring and how much from the group of smaller springs to the north. There are also four other springs located around the catchment – mostly to the south of Tobermore. There are sporadic discharge records for these springs.

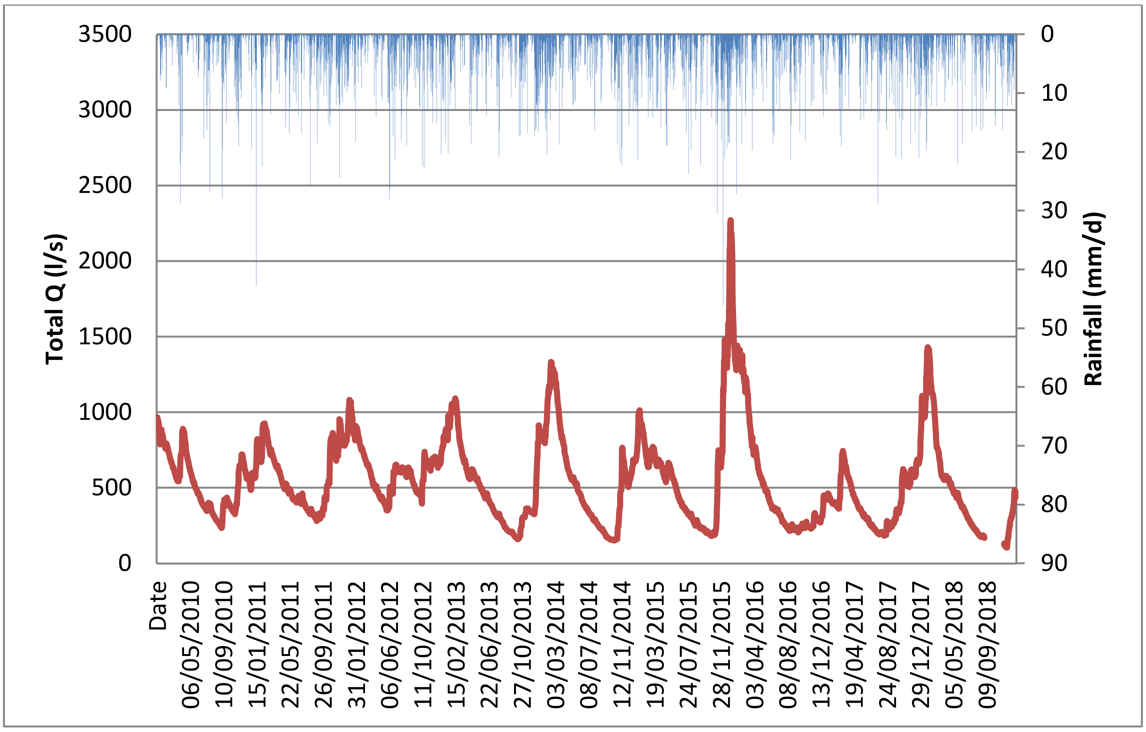


Figure 22: *A sample hydrograph for Killeglan Spring plotted against daily rainfall values*

As previously mentioned, the spring has had water quality issues and the water was not fit to drink for the 7,000 custumers. A 'boil water notice' was in place from 2009 to 2015. The main water quality issues were mostly microbiological with consistent levels of coliforms and spikes of cryptosporidium and Clostridium perfringens in the supply. There were also some chemical excedeences. The water treatment was inadequate to deal with gross exceedences in raw water quality. It has since been upgraded with treated water now reaching the required standard (*Figure 23*).

Figure 23: *Aerial view of the upgraded Killeglan Spring and drinking water treatment plant.*

6.7 Data available for the project

The data and map layers presented in this report are available for the study area. Datasets such as aquifer classification, groundwater vulnerability, subsoil permeability and type, Quaternary data and recharge data are available at a 1:50,000 scale, bedrock data is available at 1:100,000 scale. Data in the karst landform database and the water tracing database are generally located to 10-50 m.

Spring discharge measurements for Tobermore Spring and the springs to the north, have been recorded since August 2001 and are currently ongoing (*Figure 22*). The readings are taken at 15 minute frequencies. There are some small data gaps in this record. It is monitored as part of the EPA hydrometric network. The EPA currently has 703 active stations, 603 of these have continuous water level monitoring and 20 of these are karst springs. As part of this programme, water quality samples are taken 2-4 times a year. There are only infrequent spot discharge measurements for the remaining, smaller springs in the catchment.

Existing water quality data dates back from November 1995 but these are spot measurements taken a few times a year. The spring was continuously monitored for water quality parameters between October 2009 to April 2012 (*Figure 24*). Temperature, specific conductivity, pH, dissolved oxygen and turbidity were recorded on an hourly basis. There is a question mark over the reliability of some of these data due to instrument drift (Tedd, 2013). More recently, the spring is managed by Glen Aqua for Irish Water. They have continuous hourly readings for EC, temperature, DO, pH and turbidity. They also monitor both the raw and treated water for various microbiological and chemical parameters. The frequency of this monitoring is not yet understood, but it is at least once a month.

Killeglan Spring: Tobermore Spring and springs to the north			
Data type	Time step	Monitoring period	Time period
Discharge	15 mins	18 year	August 2001 - ongoing
Electrical conductivity	1 hour	6.7+ year (2.7 year and 4+ years)	Oct 2009 – April 2012 2015 - ongoing
Temperature, DO, pH, Turbidity	1 hour	6.7+ year (2.7 year and 4+ years)	Oct 2009 – April 2012 2015 - ongoing
Major anions/cations	2-5 times a year	11 year	June 1995 - 2006
Major anions/cations	12 times a year	4 year	2015 - ongoing
O, H stable isotopes			
TOC	2-5 times a year	9 years	June 1997 - 2006
TOC	12 times a year	4 year	2015 - ongoing

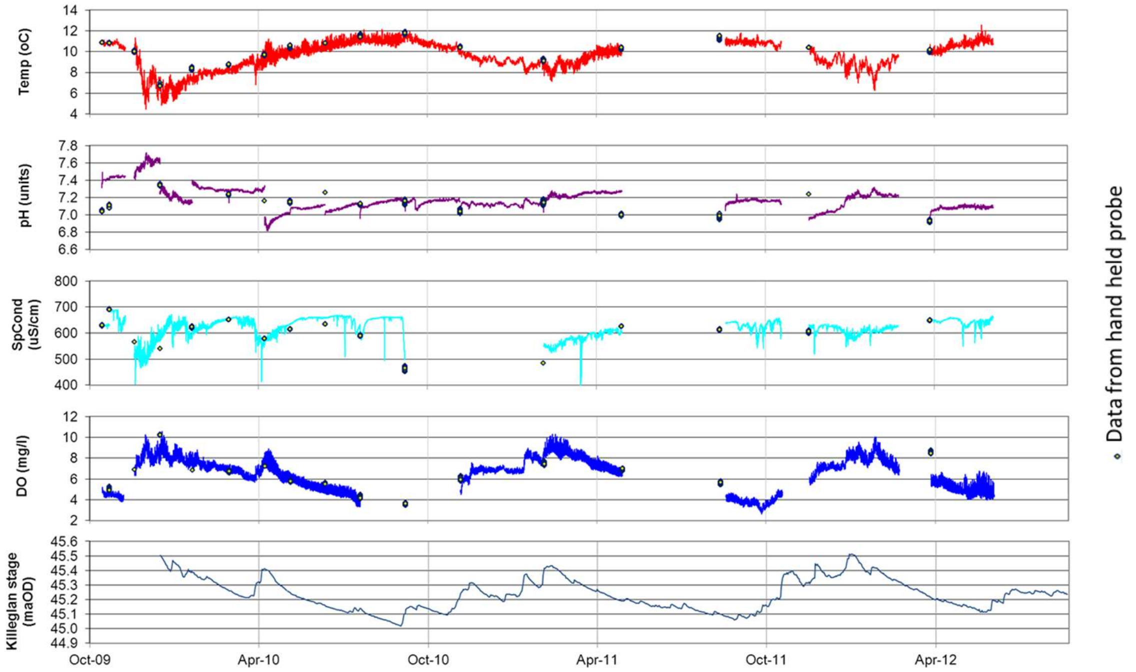
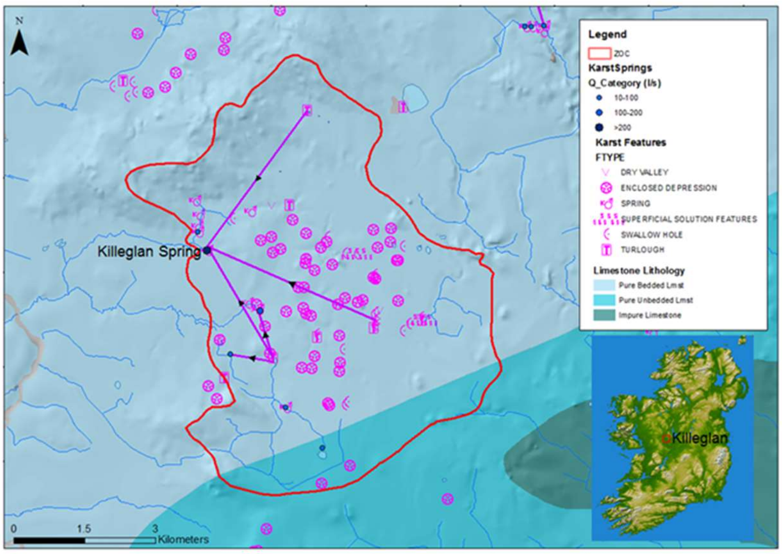


Figure 24 : Killeglan probe parameters plotted with stage (Tedd, 2013)

6.8 Summary

<table>
<tr><td>Pilot name</td><td colspan="3">Killeglan Spring</td></tr>
<tr><td>Country</td><td>Ireland</td><td>EU-region</td><td>Atlantic lowland</td></tr>
<tr><td>Area (km^2)</td><td>42</td><td>Lithology</td><td>Limestone</td></tr>
<tr><td>Short description:
The Killeglan spring is situated in the low-lying central plain of Ireland. It is made up of a group of springs; the largest being used a drinking water supply for the region. The spring has had water quality issues due to poor bacteriological water quality and lack of adequate treatment.</td><td colspan="3">


</td></tr>
<tr><td>Monitored objects</td><td colspan="3">springs</td></tr>
<tr><td>Monitored data</td><td colspan="3">Discharge, temperature, electrical conductivity, turbidity, major cation and anions</td></tr>
<tr><td>Contact person</td><td colspan="3">Caoimhe Hickey (Caoimhe.Hickey@gsi.ie)</td></tr>
</table>

6.9 References

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7 CATALONIA: THE ST. QUINTI AND CARDENER SPRINGS

7.1 Overview

The ‘St. Quintí spring’ and ‘Cardener springs’ area located inside the hydrological system of the Port del Comte Massif (PCM), a high mountain karst aquifer (HMKA) formed by Lower Eocene fissured and karstified limestones and dolomites. The HMKA is located in the southernmost part of the Catalan Pyrenees (northeastern Spain). The elevation of the massif ranges from 900 m a.s.l. to 2387 m a.s.l. The area of the massif occupies approximately 100 km^2. The watershed of the massif divides the river basin of the Cardener River at the E and S and the river basin of the Segre River at the NW and SW. The hydrological system mainly discharges through the ‘Cardener’ springs (at the E) into the homonym river (which is the main tributary of the Llobregat River, the first water resources provider to the city of Barcelona, in NE Spain); and through the ‘St.Quintí’ spring (at the SW) which discharge to the ‘Ribera Salada’ basin in SW, tributary to the Segre River and finally to the Ebro Basin. The mean groundwater discharge of (~15 hm^3/yr) postulates this aquifer as one of the most important HMKA of the eastern Pyrenees.

7.2 Geology

The HMKA belongs to the PCM thrust sheet that presents complex structural relationships in its contours. On the E, the PCM mantle borders on the mantle of Cadí, coinciding with the point of origin for the Cardener River and the position of the ‘Cardener springs’ (spring S-04; *Figure 25*). To the NE and NW, the PCM is limited by the tectonic plates of the mantles Montsec and Boixols thrust sheets. To the S, the PCM mantle overlaps with the conglomeratic materials of the Ebro Basin, the southern foreland basin of the Pyrenees. The internal structure of the PCM mantle is formed by a set of folds and thrusts detached above the Triassic. These folds have a constant direction NE-SW parallel to the NW limit of the mantle (Vergés, 1999). The stratigraphic series contains materials from the Triassic, Jurassic, Cretaceous and Paleogene (Eocene-Oligocene) with a total of more than 1300 m thickness at the top. The PCM constitutes an independent structural and regional hydro-geological unit and contains one of the most important karst aquifers of the Catalan Pyrenees, formed by Lower Eocene – fissured and karstified limestones and dolomites.

7.3 Geomorphology

From the geomorphological point of view, the PCM has a smooth rounded landscape with a plain in the highest part without vegetation cover and with almost no soil, which corresponds to approximately 10% of the total area. The rest of the massif is covered by mountain meadows (29%) and forest (61%) with scarce soil depth up to medium developed soil cover. Different karstic forms progressively appear from 1950 m a.s.l. upwards, being well developed at 2050 m a.s.l., (see *Figure 25*, indicated as ‘Area with well-developed karst landforms’) with sinkholes, dry caves, dolines and karren fields, generating a heterogeneous karstified hydrogeological system.

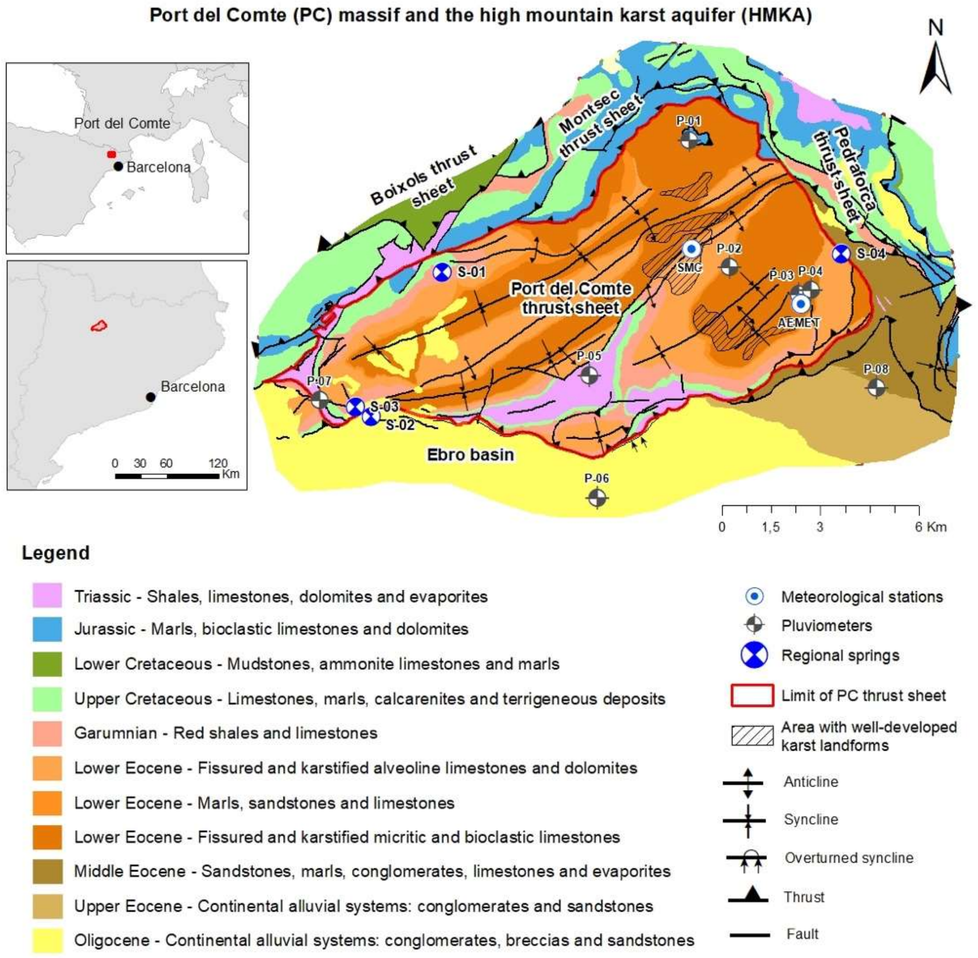


Figure 25: Geological map of the PCM and the location of 'St. Quintí spring' (S-02) and 'Cardener spring' (S-04) (modified from ICGC, 2007). P-0X indicates the position of eight temporal pluviometers implemented to collect rain water samples and used for the period des13 – des15. There are two official meteorological stations, one from AEMET (Spanish Meteorological Agency) and the other from SMC (Meteorological Service of Catalonia).

7.4 Climate

From a climatic point of view, and according to the Köppen-Geiger classification (Peel et al., 2007), the study zone has a cold climate without dry season and temperate summer. At the meteorological station SMC (*Figure 25*), which is located at 2315m a.s.l., the average values of precipitation, temperature and potential evapotranspiration calculated with the 'Hargreaves' method are 1055 mm/yr, 3,24 °C and 525 mm/yr, respectively. The snow cap is present in the upper zones of the basin in winter and spring, maintained annually for 3 to 4 months since 1800m a.s.l., meaning that precipitation is partly produced as snow. Despite the high average rainfall above 1000 mm/yr, in most of the area the surface runoff is almost nonexistent due to the epikarst development in these altitudes, and it is not observed until reaching lower altitudes.

7.5 Hydrogeology

The geologic structure and stratigraphy of the PCM thrust strongly influence the location of the existing karst springs, their groundwater geochemistry and their hydrologic behaviour. The lower Upper Cretaceous/Paleocene (Garumnian facies) substrate materials underlying the Lower Eocene karstic aquifer are composed of sandstone, siltstone and shale. These materials constitute an impervious layer for the overlaying aquifer system.

The hydrogeological conceptual model of the PCM aquifer system considers that recharge is produced by infiltration of precipitation as rainfall and snowmelt. The magnitude and distribution of infiltration is conditioned by the development of the karst landforms. The infiltration is produced: 1) in a concentrated way through the local karstic elements such as dolines and, 2) in a diffuse way by rain and snowmelt along the whole PCM area. The infiltrated water flows vertically through the unsaturated zone (NSZ) towards the saturated zone. The hydrogeological system naturally discharges through a large number of existing springs of different entity. Approximately 100 springs have been found in the PCM showing large discrepancies in their mean discharge flow rate, ranging from values <<0,1 l/s up to values > 100 l/s. Most of these springs discharge small-scale local sub-surface water flows that often re-infiltrate or are captured for small uses. The main groundwater discharge points of the hydrogeological system are four springs: the 'Aiguaneix spring', 'St. Quintí spring', 'Can Sala spring' and 'Cardener spring' (S-01, S-02, S-03 and S-04 in *Figure 25* respectively). There is also a diffuse discharge of groundwater to the north through the 'Riu Fred' sub-basin that should help to drain the system. Of the four springs, the 'Cardener spring' and 'St. Quintí spring' are the main. Their inferred catchment areas by means of integrated modelling (Herms, 2019) represents more than 44 km^2. (*Figure 26*). All of them have been monitored regularly between set 2013 until oct 2015, showing that they have a highly variable discharge flow rate (*Figure 27*). The four springs discharges the system approximately at elevation of 1000 a.s.l. and specifically, the 'Cardener spring' and 'St. Quintí spring' are located at 1032m a.s.l. and 944 m a.s.l. respectively. Through these two main springs, the hydrogeological system discharges at two principal watersheds: the Cardener River watershed to the east and the Segre River watershed to the northwest. Groundwater flow direction is conditioned by the geological structure of PCM.

The analysis of stable isotopes for the period between set2013 until oct2015 indicates that the range of recharge altitudes for both springs vary slightly: for 'St. Quintí spring' are suited between 1750m a.s.l. to 2300m a.s.l. with a main elevation estimated at 2038m a.s.l. according to a regression model (Herms, 2019), whereas for the 'Cardener spring' are suited between 1925m a.s.l. to 2250m a.s.l. with a main elevation estimated at 2099m a.s.l. The exact position of the regional groundwater table in the aquifer is not known. There are only 2 water wells located just at the boundaries of the system that pump very low rates for drinking purposes. There aren't water wells or piezometers inside the aquifer. Only in 2002, a water well was drilled for a particular purpose to a depth of more than 400 m from 1700 m.a.s.l. which not only found the phreatic level, but intense karstification was observed. Although no tracer tests are available for this aquifer (task that remains for future field-works), it is estimated that the value of effective porosity for the massif must be high. Applying the hydraulics principles of the KARSYS approach (Jeannin et al. 2012, and others) -which assumes that the volume below the main perennial spring in well-developed karst aquifers is normally water saturated, and that the expected high degree of karstification cause the hydraulic gradients upstream from the karst springs at low-water stage could be close to 0% or a 1% at most - the regional saturated zone for the PCM aquifer could be situated between 1000m a.s.l. to 1100m a.s.l. Consequently, the epikarst NSZ in the highest areas of the PCM may presents a thickness close to 1000m.

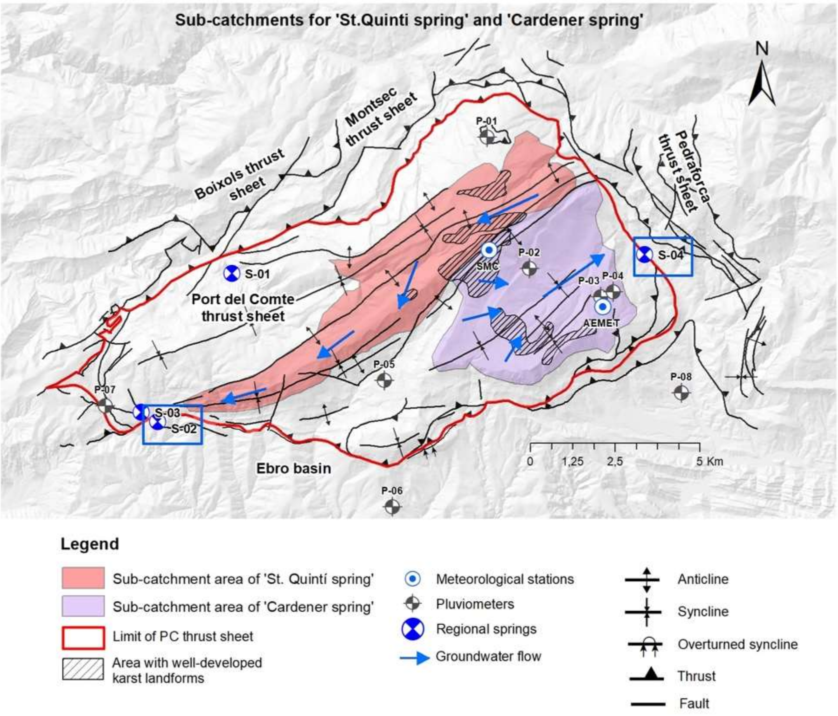
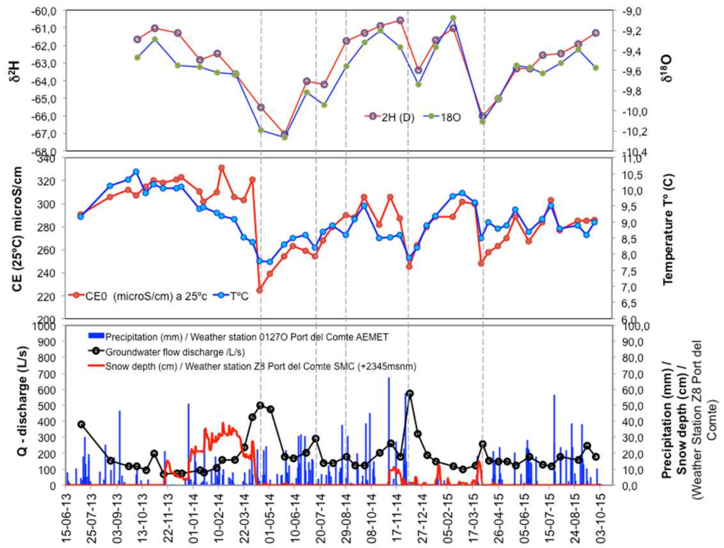


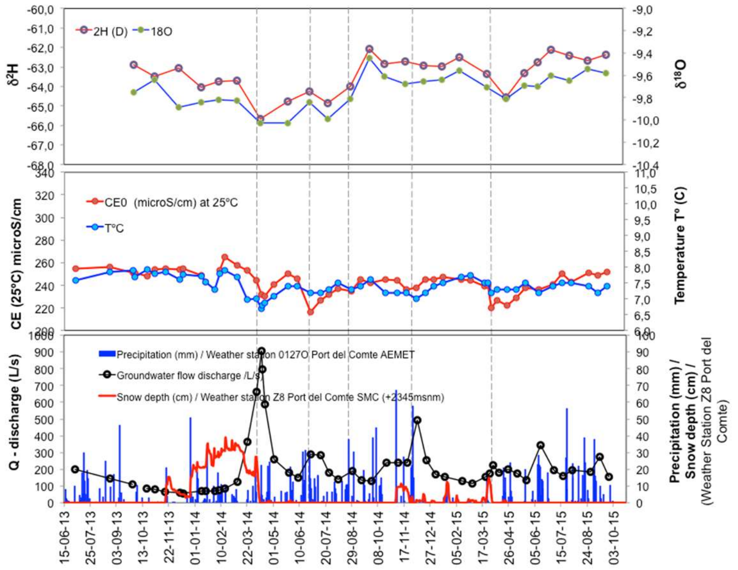
Figure 26: Scheme of the 'St. Quintí spring' and 'Cardener spring' catchment and discharge areas (Herms, 2019).

7.6 Hydrodynamic characteristics of the springs

The flow rates measured in the karst springs at 'St. Quintí spring' and 'Cardener spring' vary widely in dependence on climatic conditions and above all as a function of the snowmelt periods *Figure 27*). For the 'Cardener spring', the dataset available from its old gauge station (ACA, 2010) for the period between 2000 until 2010, indicates that the flow rate ranged between 58 l/s and a punctual value of 4018 l/s (May 2001), with an average of 325 l/s. For the monitored period between set2013 until oct2015 (Herms 2019), the flow rate ranged between 58 l/s and 903 l/s, with an average of 221 l/s (the maximum was registered in April 2014 just after the beginning of the snowmelt period). For the 'St. Quintí spring', the flow rate for the monitored period between set2013 until oct2015 ranged between 70 l/s and 575 l/s, with an average of 189 l/s (the maximum was also registered in the same moment as the 'Cardener spring' just after the beginning of the snowmelt period). For both springs, during dry periods, the flow rates almost reach a steady state. The discharge hydrographs for the same period show, in general terms, the same tendency. Nevertheless, although the 'Cardener spring' has greater flow rate oscillations (58-903 l/s vs. 70-575 l/s), the hydro-geochemistry in the 'St. Quintí spring' shows a slightly greater seasonal variability (e.g. the CE and T^{o} for 'St. Quintí spring' varies between 221-331 μS/cm and 7,7 -10,5 ^{o}C whereas for 'Cardener spring' between 216-265 μS/cm and 6,7 -7,92 ^{o}C, which is as a proxy among other that it receives recharge water from a little lower altitudes.



Manantial M-43 Font de Sant Quintí. Evolución contenido isotopico δ^2H / $\delta^{18}O$



Manantial M-22 Fonts del Cardener. Evolución contenido isotópico δ^2H / $\delta^{18}O$

Figure 27: Hydrodynamic and physic-chemical graph data (CE, T, stable isotopes) of the 'St. Quintí spring' and 'Cardener spring' for the period jul13 -oct15 (Herms, 2017)

7.7 Data available for the project

1. St. Quintí Spring (Z - 1032m a.s.l.)			
Data type	Time step	Monitoring period	Time period
Flow-rate	fortnightly	2 years	Jul2013 – Oct2015
Tº, Eh, Ph, CE, TDS	fortnightly	2 years	Jul2013 – Oct2015
Major anions/cations	monthly	2 years	Set2013 – Oct2015
Trace metals	monthly	2 years	Set2013 – Oct2015

Nutrients (*)	monthly	2 years	Set2013 – Oct2015
Stable isotopes (**)	monthly	2 years	Set2013 – Oct2015

2. Cardener Spring (Z - 944m a.s.l.)			
Data type	Time step	Monitoring period	Time period
Flow-rate	fortnightly	2 years	Jul2013 – Oct2015
T°, Eh, Ph, CE, TDS	fortnightly	2 years	Jul2013 – Oct2015
Major anions/cations	monthly	2 years	Set2013 – Oct2015
Trace metals	monthly	2 years	Set2013 – Oct2015
Nutrients (*)	monthly	2 years	Set2013 – Oct2015
Stable isotopes (**)	monthly	2 years	Set2013 – Oct2015

(*) NO_3^-, NO_2^-, NH_4^+ (**) δ^2H_{H2O}, $\delta^{18}O_{H2O}$

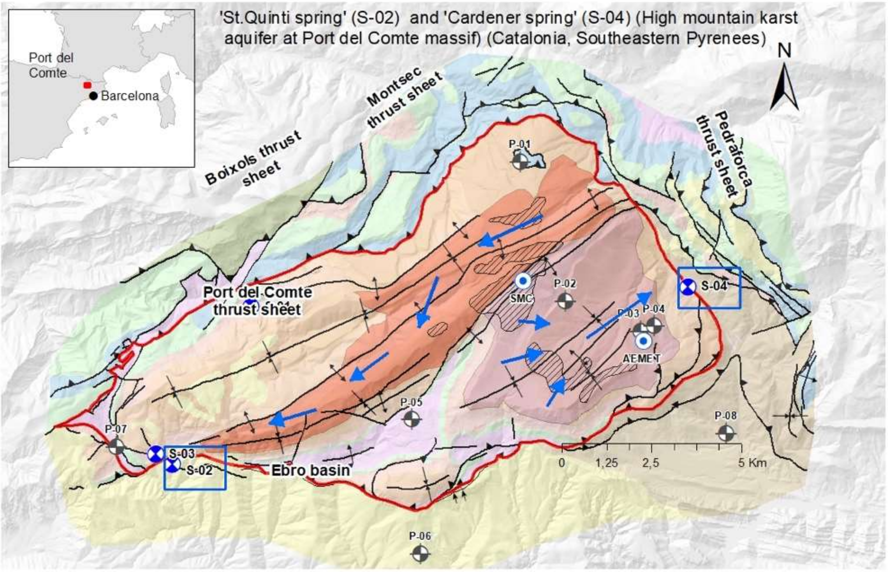
3. AEMET-0127O Metereological station (Z - 1800m a.s.l.)			
Data type	Time step	Monitoring period	Time period
Precipitation	daily	> 10 years	Jan 1996- Apr 2016
Temperature	daily	> 10 years	Jan 1996- Apr 2016

4. SMC Z8 Metereological station (Z - 2315m a.s.l.)			
Data type	Time step	Monitoring period	Time period
Precipitation	daily	> 10 years	Oct 2002- Apr 2016
Temperature	daily	> 10 years	Oct 2002- Apr 2016

In addition, there are available the following information:

- Few samples and chemical data from precipitation water (snow) are available.
- Data from stable isotopes from 8 temporal rain gauges at quarterly basis from the period des2013 – des2015 are also available.
- For the Cardener spring, discharge data for two long periods with small gaps: a) period 27th February 1985 until 1st Oct 1996, b) 5th Sep 2000 until 1st Dec 2010 (daily) are also available.
- Monitoring objects are shown in Figure 1.

7.8 Summary

Pilot name	**The 'St. Quintí and Cardener springs' (Port del Comte Massif (PCM) hydrological system (Catalonia, Southeastern Pyrenees, NE Spain)**		
Country	Catalonia, Spain	EU-region	Southeastern Pyrenees Mountains
Area (km^2)	100 (for the whole PCM) 44 (both springs catchment areas)	Lithology	Limestone and dolomite
Short description: 'St. Quintí spring' (M-43 in the figure) and 'Cardener springs' (M-22) are the main discharge points of the Port del Comte karst hydrogeological system. Flow rates of both spings widely according to the snowmelt periods.			
Monitored objects	Springs (two), Metereological station (two), Temporal pluviometers (eight)		
Monitored data	Discharge flow rates, groundwater temperature, EC, Ph, CE, chemistry (major ion, trace elements, incluiding nutrients), isotopic composition (δ^2H_{H2O}, $\delta^{18}O_{H2O}$ either from groundwater and precipitation), and precipitation and temperature values from two meteo stations.		
Contact person	Ignasi Herms (ignasi.herms@icgc.cat)		

7.9 References

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8 UK: BEDHAMPTON AND HAVANT SPRINGS

8.1 Overview

The Bedhampton and Havant springs are located in southern England, within the county of Hampshire. They are often referred to as a 'spring complex' as they are made up of over 28 discrete springs that issue along a 1.5 km east–west trending line (Jones and Robins, 1999). The average combined discharge of the springs is 94 Ml/day (James Bucknall, personal communication 2017). The springs sustain a major public supply to the surrounding areas, including the city of Portsmouth.

The Cretaceous Chalk forms a principal aquifer under much of the South East of England, including beneath the Bedhampton and Havant Springs. It has a high transmissivity due to an extensive fracture network which is enhanced by dissolutional processes. The Chalk in this region displays classic signs of karst, including dissolutionally enlarged cavities, dolines, solution pipes and stream sinks (McDowell et al., 2008; Barton et al., undated). A series of tracer tests conducted in the region, primarily injected into swallow holes, suggest groundwater velocities of up to 12.30 km/day, over distances of up to 6.6 km (Price, 1979; Barton et al. undated).

8.2 Geology

The Cretaceous Chalk is the major aquifer in this region of the UK, with the Bedhampton and Havant springs issuing from its upper formations. Palaeogene sediments from the Lambeth Group and London Clay Formation overlie the Chalk in areas. Parts of the Chalk outcrop are covered in even younger superficial deposits such as alluvium and the Clay-With-Flints Formation, the latter is reworked Palaeogene material.

The Chalk in this region is formed of the White Chalk Sub-Group which consists of 5 independent Formations (*Figure 28*), and known for its high density of stratigraphic features including flint bands, marl seams and hard grounds. Fractures are also common, and often found with increased aperture due to dissolution. The nature of the fractures and inception horizons are dependent on the local hydrogeological conditions. *Figure 28* shows the dominant lithology in the Bedhampton and Havant area.

Group	**Formation**	**Lithology**
Thames Group	London Clay Formation	Clay, some silt and sand and pebbles
Lambeth Group	Reading Formation	Clay and sand
White Chalk Subgroup	Newhaven Chalk Formation	Soft to medium hard smooth white chalk with numerous marl seams and flint bands.
	Seaford Chalk Formation	Firm white chalk with large nodular and tabular flints.
	Lewes Nodular Chalk Formation	Hard to very hard nodular chalks with interbedded soft chalk and marls.
	New Pit Chalk Formation	Firm and blocky white chalk with sporadic flint and numerous marls.

	Holywell Nodular Chalk Formation	Hard nodular chalk with thin marls and often significant shell debris.

Figure 28: Table of lithology of the Bedhampton and Havant spring complex

The geological structure of the area is dominated by the east-west trending Chichester Syncline (*Figure 29*). The Chalk outcrops to the north and southwest of the syncline, and superficial deposits outcrop in the centre. The springs at Bedhampton and Havant are situated within the upper part of the Chalk group on the steep northern limb of the Portsdown anticline (*Figure 29*).

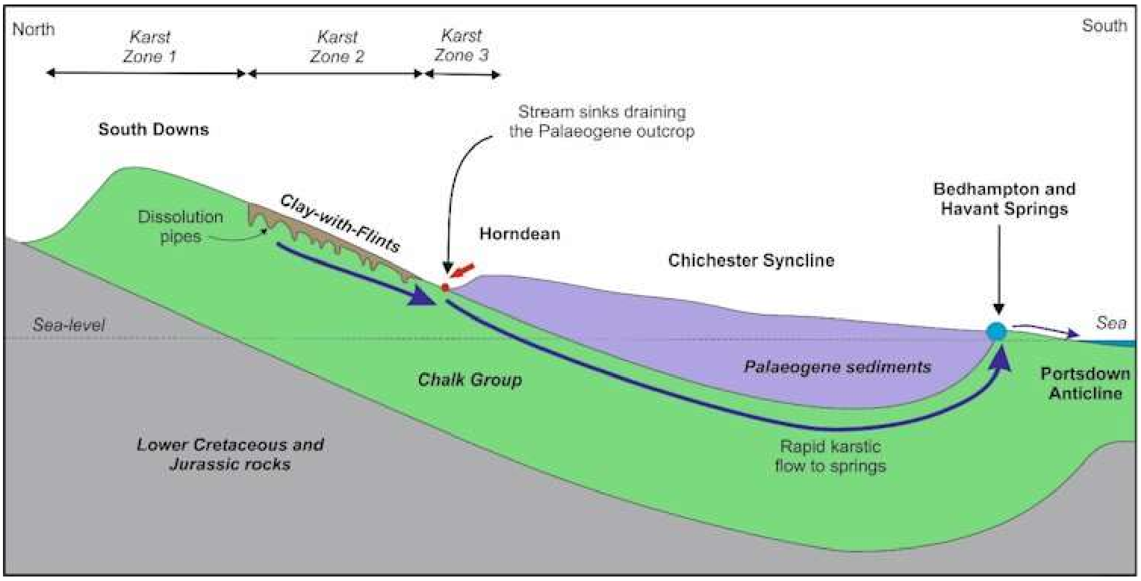


Figure 29: Schematic cross-section of the Chichester Syncline. Geological material © NERC. All rights reserved. Topography © Crown Copyright reserved.

8.3 Geomorphology

Surface karst features are observed in abundance in the Bedhampton and Havant area, suggesting the presence of well-developed karstic networks. Barton et al. (undated) state that there are around 50 stream sinks within the Bedhampton and Havant area. Stream sinks in outcrops of the Chalk mostly occur near the boundary with the Palaeogene formations due to focused infiltration into the Chalk where water drains off these impermeable beds (Maurice et al., 2017). Stream sinks are important points of recharge into the Chalk aquifer, especially as there are no permanent streams in the area.

Dolines are common features in the Cretaceous Chalk and are generally associated with the Chalk-Palaeogene boundary. They may be abandoned stream sinks or other types of dolines (Maurice et al., 2017). There are more than 300 recorded “surface depressions” in the Bedhampton and Havant area, from BGS, EA and Portsmouth Water records. It is extremely difficult to distinguish between karst dolines and manmade pits in the Chalk and surface depressions may not all be karst solution features. The density of dolines is reported to be significantly larger than the remaining South Downs Chalk, with a density of solution features of 55 per km^2 near Rowlands Castle and Horndean, compared to an average 15 features per 100 km^2 across the South Downs (McDowell et al., 2008). Dissolution pipes are also common in the Chalk. BGS hold no record of dissolution pipes in the Bedhampton and Havant area. However, they are likely to be present, especially on the northern limb of the Chichester Syncline (*Figure 29*) where the Chalk is overlain by the Clay-with-Flints formation, but may have no surface expression. Dry valleys also occur within the catchments.

8.4 Climate

The UK is split into a number of climate zones, with the Bedhampton and Havant spring complex lying within the 'Southern England' zone. In this zone the mean annual temperatures vary between 11.5°C in central London and along the southern coast, to 9.5°C inland (Met Office, 2016). This is slightly higher than the UK average between 7 and 11°C.

Bedhampton and Havant, are not far from the wettest areas in the South Downs and the higher parts of Dorset, which have an average of over 950 mm of rain per year. The driest parts of eastern England get only 500 mm per year (Met Office, 2016). Prolonged rainfall can lead to widespread flooding especially when the soils are near saturation, making it prone to flood events.

8.5 Hydrogeology

Groundwater levels indicate that regional groundwater flow is focused towards the Bedhampton and Havant springs. The Chichester Syncline acts as a barrier to groundwater flow through the Chalk (Jones and Robins, 1999) deflecting groundwater flow beneath the Palaeogene deposits coastward from the topographic highs of the South Downs. It is likely that the Chalk is intensely fractured in this area, allowing groundwater movement across the Chichester syncline (Day, 1964).

Substantial proportions of groundwater flow in karstic areas is through solutionally enhanced fissure networks. Stream sinks are important points of recharge for the aquifer as there are no permanent streams in the area. Flow into some nearby stream sinks were measured by Portsmouth Water in 1961 and recorded flows of more than 7 Ml/day into single sink holes (Price 1979).

Tracer testing described in Atkinson & Smith (1974) aimed to establish a potential connection between swallow holes associated with the Cretaceous-Palaeogene boundary and the Bedhampton and Havant spring complex. The tracer tests demonstrated rapid groundwater flow, with first arrival velocity of 2.60 km/day at Bedhampton and 2.08 km/day at Havant (Atkinson & Smith, 1974). Dye tracers were used and first detected at Bedhampton springs, 5750 m from the injection site 53 hours after injection, giving a calculated velocity of 2.60 km/day. The first detection at Havant springs, 5800 m from the injection site was 67 hours after injection, giving a velocity of 2.08 km/day. A total of 69.7% of the tracer was recovered, 69.1% was recovered at Bedhampton springs and 0.6% recovered at Havant springs, implying a stronger connection from Hazelton Wood Swallet to the Bedhampton springs than to the Havant springs. Atkinson & Smith (1974) concluded that it is possible that the two springs drain different parts of the Chalk, but are connected by fractures near the springs which results in some mixing. The theory is backed up by the water quality records from Portsmouth Water, which highlight different responses to rainfall of dissolved solids and turbidity in the springs at Bedhampton and those at Havant (Atkinson & Smith, 1974).

Eight further connections were identified in 1978 between four stream sinks on the northern limb of the Chichester Syncline and the Bedhampton and Havant springs over distances of 4.6

to 6.6 km, the results of which are discussed in Price (1979) and Barton et al. (undated). The tracer tests show that fast preferential flow routes that occur in the Chalk are commonly associated with close proximity to the Palaeogene cover, where the surface karst features are primarily located (Allen, 1995). The most westerly stream sink (No. 13) showed no connection to either the Bedhampton or Havant springs. Three others showed connections to both Bedhampton and Havant springs, but with varying velocities and recovery rates. Out of the three, the westerly stream sink (No. 26) recorded a first arrival at Bedhampton 57 hours after injection, with a flow velocity of 2.65 km/day, and to Havant after 50 hours at 3.17 km/day. Of a total 8.8% tracer recovery, 7.9 % was recovered at Bedhampton and 0.9% at Havant. The central stream sink (No. 41) was first detected at Bedhampton after 27 hours and at Havant after 35 hours. Groundwater velocities determined from this test were therefore 5.07 km/day from No. 41 to Bedhampton and 4.00 km/day to Havant. Of the 49.6% recovered tracer, 39.7% was recovered at Bedhampton, while only 9.9% was recovered at Havant. The most easterly stream sink (No. 39) located between 4.6 km and 4.8 km from the springs recorded velocities of 10.5 km/day to Bedhampton and 12.3 km/day to Havant (based on first arrival times). The total calculated recovery for this test was 38.4%, with 23.2% recovered at Bedhampton and 15.2% at Havant.

8.6 Hydrodynamic characteristics of the springs

The discharge data available for the Bedhampton and Havant springs is on a weekly timestep, and is corrected for the influence of a nearby abstraction. Between 1908 and 2016 the average combined discharge of Bedhampton and Havant springs was 94 Ml/day where the minimum weekly average yield was 53 Ml/day and the maximum was 169 Ml/day. However, we hold no discharge data for the separate springs.

Turbidity data are available at roughly a weekly timestep from January 2001 to January 2019. Turbidity in the Bedhampton and Havant springs has been observed by Portsmouth water to be caused by turbid water entering the karstic network via stream sinks situated to the north of the springs. Coincidence between the turbidity in the springs and significant rainfall events was previously noted and discussed in Price (1979).

Coliform data are available at roughly a weekly timestep from January 2001 to November 2018. High coliform counts are indicative of short groundwater residence times. At Bedhampton approximately 29% of samples recorded over 100 NO/100 ml, with 6% of these greater than 1000 NO/100 ml. Seasonal fluctuations are observed, with higher coliform counts observed during the wetter winter months. A similar distribution of data is observed at the Havant springs.

8.7 Data available for the project

1. Bedhampton springs			
Data type	Time step	Monitoring period	Time period
Discharge (combined for B & H)	Weekly	107.5	01/1908 – 04/2016
E.Coli	4-7 days (Weekly)	18 years	01/2001 – 11/2018
Total coliforms	4-7 days (Weekly)	18 years	01/2001 – 11/2018
Turbidity	4-7 days (Weekly)	18 years	01/2001 – 01/2019
Pesticides (various)	1-2 per month	12 years	01/2008 – 01/2019
Electrical conductivity	4-7 days (Weekly)	18 years	01/2001 – 12/2018

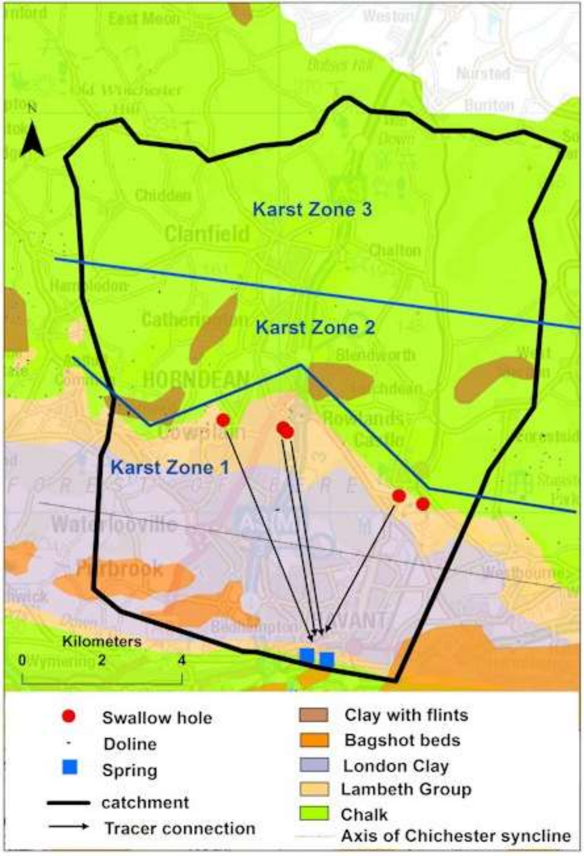
Major anions/cations	4-7 days (Weekly)	18 years	01/2001 – 12/2018

2. Havant springs			
Data type	Time step	Monitoring period	Time period
Discharge (combined for B & H)	Weekly	107.5 years	01/1908 – 04/2016
E.Coli	4-7 days (Weekly)	18 years	01/2001 – 11/2018
Total coliforms	4-7 days (Weekly)	18 years	01/2001 – 11/2018
Turbidity	4-7 days (Weekly)	18 years	01/2001 – 01/2019
Pesticides (various)	1-2 per month	12 years	01/2008 – 01/2019
Electrical conductivity	4-7 days (Weekly)	18 years	01/2001 – 12/2018
Major anions/cations	4-7 days (Weekly)	18 years	01/2001 – 12/2018

*unreliable data

8.8 Summary

<table>
<tr><td>Pilot name</td><td colspan="3">Bedhampton and Havant Springs</td></tr>
<tr><td>Country</td><td>UK</td><td>EU-region</td><td></td></tr>
<tr><td>Area (km^2)</td><td></td><td>Lithology</td><td>Chalk</td></tr>
<tr><td>Short description:

Large springs at Bedhampton and Havant have a combined average discharge of 94 Ml/day. The fast flow pathways are demonstrated by various tracer tests carried out between surface karstic features and recovered at the spring complex. High velocities and high recovery rates suggest that the springs are connected to an extensive karstic network. Correlations between high turbidity events and rainfall also suggests a link between surface karstic features and the underlying Chalk aquifer that issues in the Bedhampton and Havant area.</td><td colspan="3">

<i>Geology and karstic features of the Bedhampton and Havant area with some of the known tracer connections highlighted. Geological material © NERC. All rights reserved. Topography © Crown Copyright reserved.</i></td></tr>
<tr><td>Monitored objects</td><td colspan="3">3 sample locations</td></tr>
<tr><td>Monitored data</td><td colspan="3">Discharge, turbidity, EC, chemistry, pesticides</td></tr>
<tr><td>Contact person</td><td colspan="3">sbun@bgs.ac.uk and loma@bgs.ac.uk</td></tr>
</table>

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9 UK: ESSENDON

9.1 Overview

Essendon Pumping Station is an example of a karstic chalk borehole abstraction. The pumping station is comprised of two operational boreholes located side-by-side approximately 50 m from the River Lea (Morrison, 2017). The water supply comes from boreholes and an adit system. Over the period April 1995 to January 2019 the average daily abstraction from the Essendon boreholes was 4.11 Ml/d, reaching a maximum of 13.43 Ml/d. The large yield and geophysical logging suggest the presence of solutionally enlarged fissures within the boreholes.

Karst features are prevalent in the Essendon area (Wooldrige and Kirkaldy, 1937; Harold, 1937; Cook, 2010), and include the Water End swallow holes which are the largest karst stream sink in the English Chalk. Tracer testing from the Water End swallow holes has demonstrated connections to a range of springs and boreholes over distances of up 16.6 km with groundwater velocities of up to 3.36 km/day (Harold 1937; Cook 2010). Tracer injected at the Water End swallow holes has been detected at Essendon, with a groundwater velocity of 2.4 km/day over a distance of 6.8 km (Cook, 2010), demonstrating the extent of the Essendon catchment to the southwest.

Further insights into the hydrogeology of the area come from a detailed study of a bromate contamination event first detected in boreholes in May 2000 (Cook, 2010; Fitzpatrick, 2011; Cook et al., 2012; Wyke et al., 2013). The bromate originated from Sandridge and was widely mapped over an extensive area to the east of the source. It was detected at Essendon pumping station around 11km to the east, demonstrating that the Essendon catchment also extends to the west into an area of outcrop Chalk where surface karst features are generally absent.

9.2 Geology

Much of the Essendon catchment is overlain by superficial deposits, predominantly the Lambeth Group and London Clay Formation. The approximate thickness of superficial deposits in the Essendon region is 1-2 m. The Seaford Chalk Formation is exposed in the southern side of the Lea Valley (Farrant et al., 2017). There are also some thin layers of River terrace deposits and Alluvium, dominated by silts and sands associated with the former course of the River Thames (Farrant et al., 2017).

The Cretaecous Chalk dominates this area, and forms the principal aquifer in the south-east of England. The Cretaceous Chalk is a fine-grained and highly porous limestone comprised principally of coccolithic fragments. The boreholes at Essendon penetrate the Seaford Chalk Formation and Lewes Nodular Chalk Formation that form the upper part of the White Chalk Sub-Group. The Chalk Rock Member of the Lewes Nodular Chalk Formation is comprised of very hard chalk with some nodular and mineralised hardgrounds and marls, and can be up to 4-5 m in the Essendon region. The average total thickness of the Chalk is approximately 200-215 m in the Essendon region, thinning to the north (Allen et al., 1997).

Essendon lies to the east of the Chilterns on the northern quarter of the London Basin. The London Basin that controls the regional structure is an asymmetrical syncline with a SW-NE-east axis that dips to the east beneath London (Shand et al., 2003). The regional dip of the Chalk is less than 2^{o} down towards the Southeast (Cook et al., 2012).

Due to tectonic influences, a number of minor faults and folds exist on the main syncline of the London Basin (Shand et al., 2003). Walsh and Ockenden (1982) describe the fracture orientation at Essendon to be dominantly NE-SW striking, with a sub-ordinate NW-SE striking set. A number of N-S aligned fracutures at Essendon suggests N-S faulting in the area (Cook, 2010).

9.3 Geomorphology

The Essendon boreholes are at an elevation of about 50 m above Ordnance Datum (OD) in a valley location, adjacent to the River Lea. From Essendon, the groundwater fed River Lea flows towards the northeast and then the southeast. There are a number of substantial springs in the Lea valley. There are also dry valleys within the Essendon area.

Surface karst features are prevalent in the Essendon area. In the current Essendon Source Protection Zone 2, there were 5 stream sinks identified during a recent field survey (Farrant et al., 2017). A further three lie on the outskirts of the catchment and may be connected to the abstraction. (*Figure 30*) shows further stream sinks in the area, predominantly located on or near the Chalk-Paleogene boundary.

The Water End swallow holes are located approximately 6.8 km to the southwest of Essendon and form the largest stream sink complex in England (Farrant et al., 2017). Water from the Mimmshall Brook sinks into a series of over 15 karst sinkholes, the number and points vary in response to the amount of water flow from the Mimmshall Brook. Walsh and Ockendon (1982), report a mean flow of ~ 80 l/s, and suggest they have the capacity to take up to 1000 l/s, before overflowing into the Upper Colne valley. Walsh and Ockendon (1982) describe the different sink points from observations between August 1969 and January 1970 and Wooldridge and Kirkaldy (1936) describe the swallow holes in 1936.

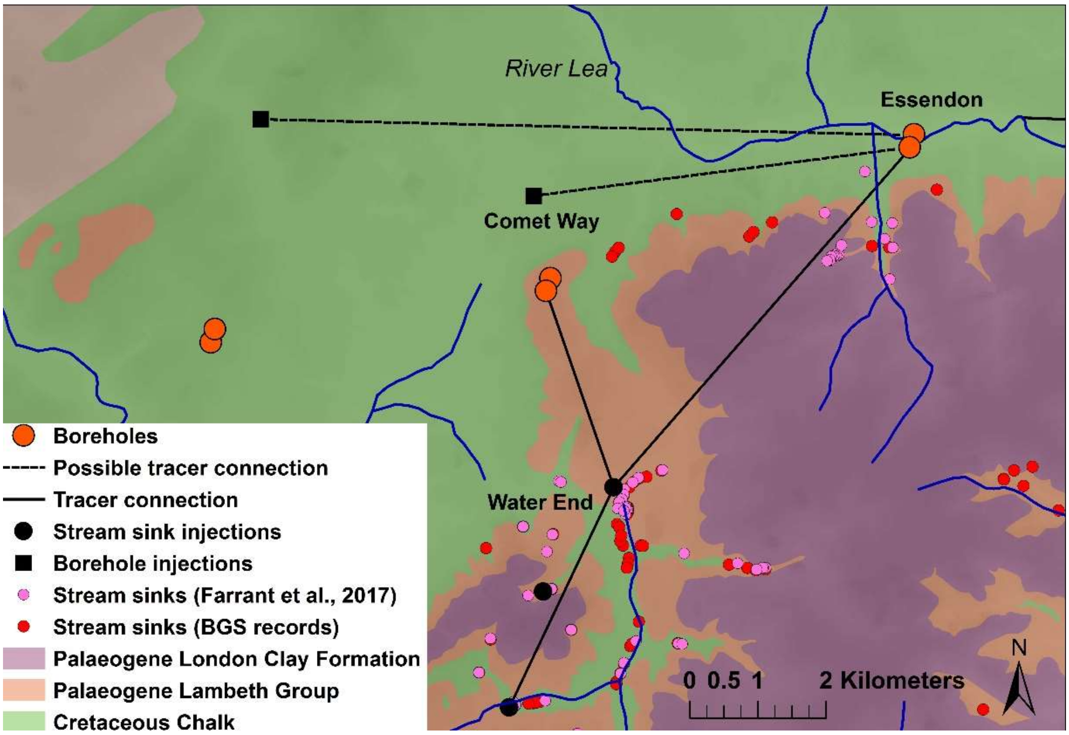


Figure 30: karstic features and tracer tests in the Essendon area. Geological material © NERC. All rights reserved. Topography © Crown Copyright reserved.

In the wider area, there are many other stream sinks which are generally associated with the Chalk-Palaeogene geological boundary (Whitaker, 1921; Farrant et al., 2017). Stream sinks represent a major point of recharge to the underlying Chalk aquifer in the Essendon region (Farrant et al., 2017). Farrant et al. (2017) identify 8 stream sinks within the SPZ 2 part of the catchment. Tracer testing has not been conducted from these stream sinks.

In the Essendon catchment few dissolution pipes have been recorded and little is known about their form. BGS hold records of two infilled dissolution pipes at ~ 1.2 km and ~ 1.8 km from the Essendon boreholes, sited on the boundary of the Chalk and Palaeogene deposits. A large number of dissolution pipes or surface depressions are recorded on the outskirts of Welwyn Garden City (~ 3 km to the north of Essendon), but little is known about their form. On the southern side of the River Lea, dissolution pipes with a length of less than 10 m are likely where river terrace deposits overlie the Chalk (Farrant et al., 2017). It is probable that karstic dissolution pipes are common in the area, particularly where the Chalk is overlain by thin Palaeogene or superficial deposits.

9.4 Climate

Essendon lies on the border between Southen and Eastern UK climate zones. In the Southern zone the mean annual temperatures vary between 11.5°C in central London and along the southern coast, to 9.5°C inland (Met Office, 2016). This is slightly higher than the UK average of between 7 and 11°C. Essendon lies close to the driest parts of eastern England which receive only 500 mm of rainfall per year (Met Office, 2016). The eastern region can be subject to dry periods and often requires water conservation measures such as hosepipe bans, particularly if recharge is low.

9.5 Hydrogeology

The Essendon boreholes and and adits intercept the Cretaceous Chalk that forms the principal aquifer in the Essendon region. The abstracted water comes from a relatively small number of inflows to the adits and boreholes. The Cretaceous Chalk is a complex aquifer in which high matrix porosity and a dense network of unmodified fractures provides substantial storage, whilst flow occurs within solutionally enlarged fissures and conduits. The Chalk Rock Member of the Lewes Nodular Chalk Formation is thought to provide the main flows to the adits and headings at Essendon (Cook, 2010). Transmissivity values are also high along the nearby River Lea, suggesting the presence of solutionally enhanced fissures and conduits (Shand et al., 2003). The hydraulic gradient in the region is oriented towards the SE, following the regional dip of the chalk.

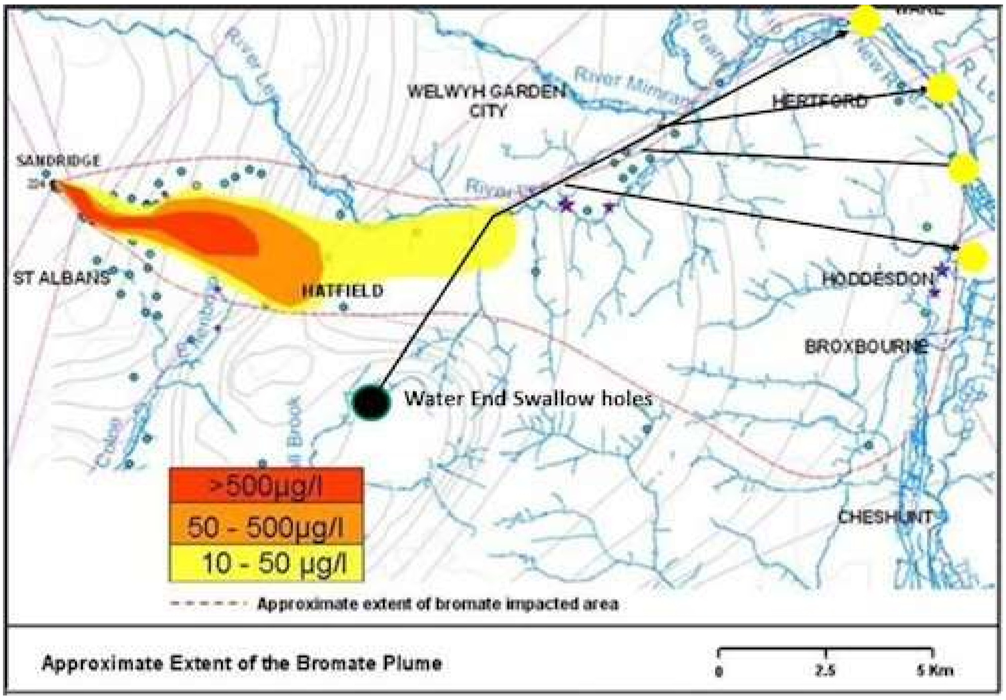
A tracer test using *Serratia Marcescens* bacteriophage demonstrated a connection between the Water End swallow holes and the Essendon boreholes over a distance of 6.8 km, with a calculated groundwater velocity of 2.4 km/day (Cook, 2010) (*Figure 30*). Tracer was also detected at two springs (Arkley Hole and Lynchmill) and four other abstractions (Amwell Marsh, Hatfield, Rye Common and Turnford), illustrating that there is a distributed network of conduits with flow down multiple flow-paths. These 6 connections had also been previously demonstrated with dyes (Harold, 1937), although Essendon was not monitored in these early tests. The tracer recovery of 4.53% at Essendon was higher than at the other sites, suggesting that the abstraction is well connected to one of the more significant conduits fed by the Water End swallow holes.

To date, there have been no tracer tests to demonstrate how the stream sinks in the Essendon catchment are related to this conduit system. Previous tracer testing from Water End has indicated a high degree of connectivity among a complex karstic network with springs and abstractions in the Essendon catchment. However, karst networks can be highly complex with isolated conduit systems, making them challenging to fully understand.

Cook (2010) also suggested a potential connection between the Comet Way borehole to the west and the Essendon abstraction. Over a distance of 5.6 km, the calculated velocity was 786 m/day based on time to first arrival. However, tracer concentrations were near background concentrations, and therefore positives are not conclusive.

The results of tracer tests reported by Cook (2010) and Harold (1937), suggest a complex and extensive conduit network in the Water End area, in which the conduit system is connected to fissures and conduits supplying abstraction boreholes as well as to karstic springs. The karstic nature of these conduits mean that travel times and recoveries are likely to vary in different seasons and under different local pumping regimes (Farrant et al., 2017).

A plume of bromate originating around 11 km to the west of Essendon and detected in May 2000 provides additional understanding of the hydrogeology of the area (*Figure 31*). The study of the plume offers insight about the transport of pollutants and the speed and direction of the regional groundwater flow. The bromate plume was widely mapped and an extensive borehole monitoring programme set up to improve understanding of the bromate distribution, and used to inform mitigation measures and reduce the threat to public water supply. Bromate was found in the Chalk bedrock matrix of cored boreholes, and it may be that storage of the bromate is predominantly in the bedrock matrix and the unmodified fracture matrix. Bromate was also detected at the springs and boreholes in the Lea valley up to 20 km from the source, demonstrating that the plume has intersected the karstic network of conduits and fissures which enables the bromate to be transported over large distances. Bromate was found at varying concentrations in nearby boreholes, with some examples of bromate free boreholes near to contaminated boreholes, demsonstrating the irregular karstic nature of the aquifer, with



different flowpaths intersected at different boreholes.

Figure 31: A plume of bromate originating near sandridge and demonstrating connectivity within the Lea Valley groundwater system. (Modified from a figure from the UK Groundwater Forum, from Cook (2010))

Bromate has also been detected at Essendon where it has been noted that seasonal fluctuations in bromate concentrations closely followed the seasonal cycle of Soil Moisture Deficit (Wyke et al., 2013). Higher bromate concentrations corresponded to dry conditions, and therefore lower groundwater levels. This suggests that under low water level conditions bromate may be transferred from storage in the matrix/unmodified fracture network into the karstic conduits and fissures through diffusion or advective mechanisms, and/or that there is more dilution of bromate during high water level conditions. Rapid responses in bromate concentrations at Essendon were observed to occur in reponse to changes in groundwater abstraction at Hatfield PWS which is 5.7 km to the southwest of Essendon (Cook et al., 2012). This suggests that there is likely to be a connected network of karstic conduits and fissures connecting these sites.

A study of the water chemistry at Essendon suggested that there was a combination of background regional groundwater and recently recharged water (Cook, 2010). The latter may reflect the known connectivity between Essendon and the Water End swallow holes, but could also indicate connectivity with other stream sinks, or with the nearby River Lea.

There remains some uncertainty about the actual catchment area of the Essendon abstraction, but evidence suggests some groundwater from the southwest via the Water End swallow holes, and contributions from the west as demonstrated by the bromate contamination.

9.6 Hydrodynamic characteristics of the borehole

Two operational boreholes at Essendon Pumping Station are used for public supply. Between 01/04/1995 and 31/01/2019 the daily average abstraction from Essendon was 4.11 Ml/day. The maximum recorded in this period was 13.43 Ml/day (July 2002). The average daily rate of abstraction has fallen since 1995.

Geophysical logging suggest that the Essendon supply comes from a small number of fissures/ small conduits. A geophysical log of borehole 3 highlights geothermal gradients at depths of 15.8 m, 20.1 m, 24.8 m, 34.0 m, 35.3 m and 38.1 m. Impeller flow logging was carried out to understand where large inflows occurred into the borehole. High flow zones were highlighted at a depth of 29-33 m (at the base of the casing) and 34.9-37.6 m, where velocity readings are between 0.75-0.95 m/min. A geophysical log and CCTV inspection of Borehole No 1 was carried out on 28/11/2000 (Morrison, 2017). Geophysical logging identified two adits to Borehole 2 and a number of smaller flow horizons. Significant turbidity is observed between the two adits, thought to be inflow of turbid waters linked to recharge events. The CCTV survey highlights high turbidity and reduced visibility at 31.5 mBD depth and 42.5 mBD, the second thought to be associated with an adit. A large fissure is observed at a depth of 57.7 mBD.

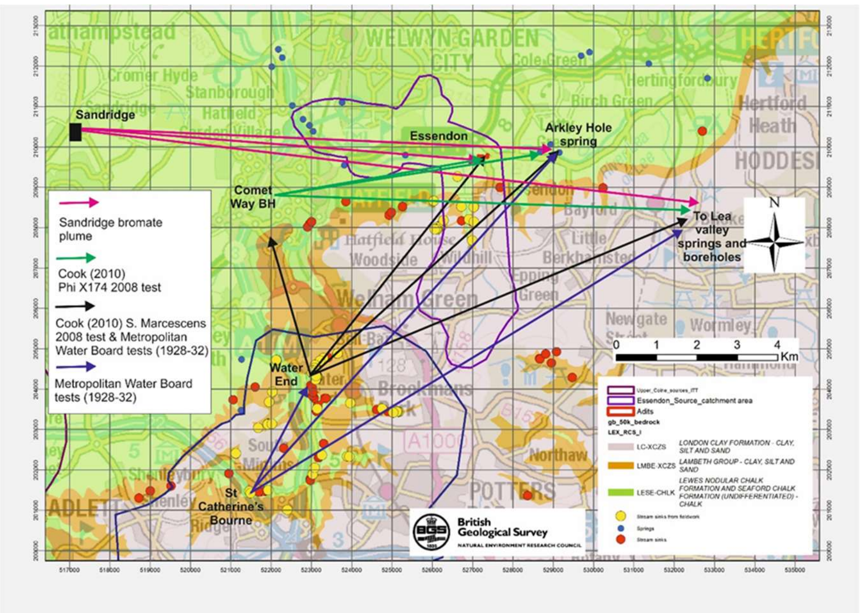
Turbidity and coliforms occur at Essendon and are known to increase following large precipitation events (Cook, 2010; Farrant et al., 2017). A large number of samples collected at Essendon contained high coliform counts (Farrant et al., 2017). More than 96% of samples had over 10 cfu/100 mls and more than 25% of samples had more than 1000 cfu/100mls. Pesticides are also found in high concentrations in water abstracted from Essendon. Concentrations are generally variable, reflecting the nature of the karst network, but peak during pestcide application (Farrant et al., 2017).

9.7 Data available for the project

1. Essendon borehole			
Data type	Time step	Monitoring period	Time period
Abstraction rates	Daily	24.5 years	04/1995 – 01/2019
Total coliforms	Variable (1-90 days)	9 years	01/2010 – 01/2019
Turbidity	Variable (1-85 days)	9 years	01/2010 – 01/2019
Bromate	Variable (1-74 days)	9 years	01/2010 – 01/2019
Pesticides and herbicides	Variable (1-149 days)	9 years	01/2010 – 01/2019
Electrical conductivity	Variable (1-320 days)	7 years	01/2013 – 01/2019
Nitrate	Variable (2-119 days)	9 years	01/2010 – 01/2019

*unreliable data

9.8 Summary

Pilot name	**Essendon**		
Country	UK	EU-region	
Area (km^2)		Lithology	Chalk
Short description: Two operational boreholes at Essendon provide an average daily yield of 4.11 Ml/day from the boreholes and an adit system. Tracer tests link the abstraction to an extensive karstic network that is fed by swallow holes at Water End. Water from Water End is also discharged at six other outlets up to 19 km away with groundwater velocities of up to 5.8 km/day. A bromate contamination event at Sandridge demonstrates that Essendon also receives water from the west in an area of outcrop Chalk away from the karst stream sinks, and provides further information on the hydrogeology of the area.	 *Selected tracer test connections in Hertfordshire, from Farrant et al. (2017), adapted from Cook (2010).*		
Monitored objects	Borehole		
Monitored data	Raw borehole data		
Contact person	sbun@bgs.ac.uk and loma@bgs.ac.uk		

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10 SLOVENIA: CLASSICAL KARST AQUIFER

10.1 Overview

The Classical Karst is a transboundary area of approx. 750 km^2 shared between Italy and Slovenia (*Figure 32*). The transboundary karst aquifer extends from Vremščica in the southeast, across Dutovlje and Komen in the east and Kostanjevica in the north, crossing the Italian border close to Doberdó and Gradisca d'Isonzo and, in the south, from Basovizza to Duino. Towns Trieste and Monflacone are situated in the southern part of Karst area.

Figure 32: Classical Karst area (source: Geopedia)

Classical Karst area is characterized by a large variety of Karst landforms. It is the most famous karst area in the world, for which the word karst was used for the first time. The Timavo spring represents the outflow of the hypogean waters present in the Classical Karst, being fed not only by precipitation, but also by the Reka river sinking in the impressive Škocjan sinkholes (UNESCO heritage since 1986), and the Soča river flowing from Julian Alps.

10.2 Geology

The Classical Karst area is built primarily of intensively karstified limestones and dolomites of Cretaceous and Paleogene age (Cucchi & Zini 2002; Jurkovšek 2008).

In the north and northeast of the aquifer, carbonate rocks are in contact with layers of Eocene flysch of low permeability from the Vipava Valley to the Trstelj Hill. In the flysch sequence sandstone, siltstone, claystone and marl are found. In the southwest the aquifer is in contact with Eocene flysch beds at the Gulf of Trieste, and in the west and southwest with alluvial deposits of the Soča River.

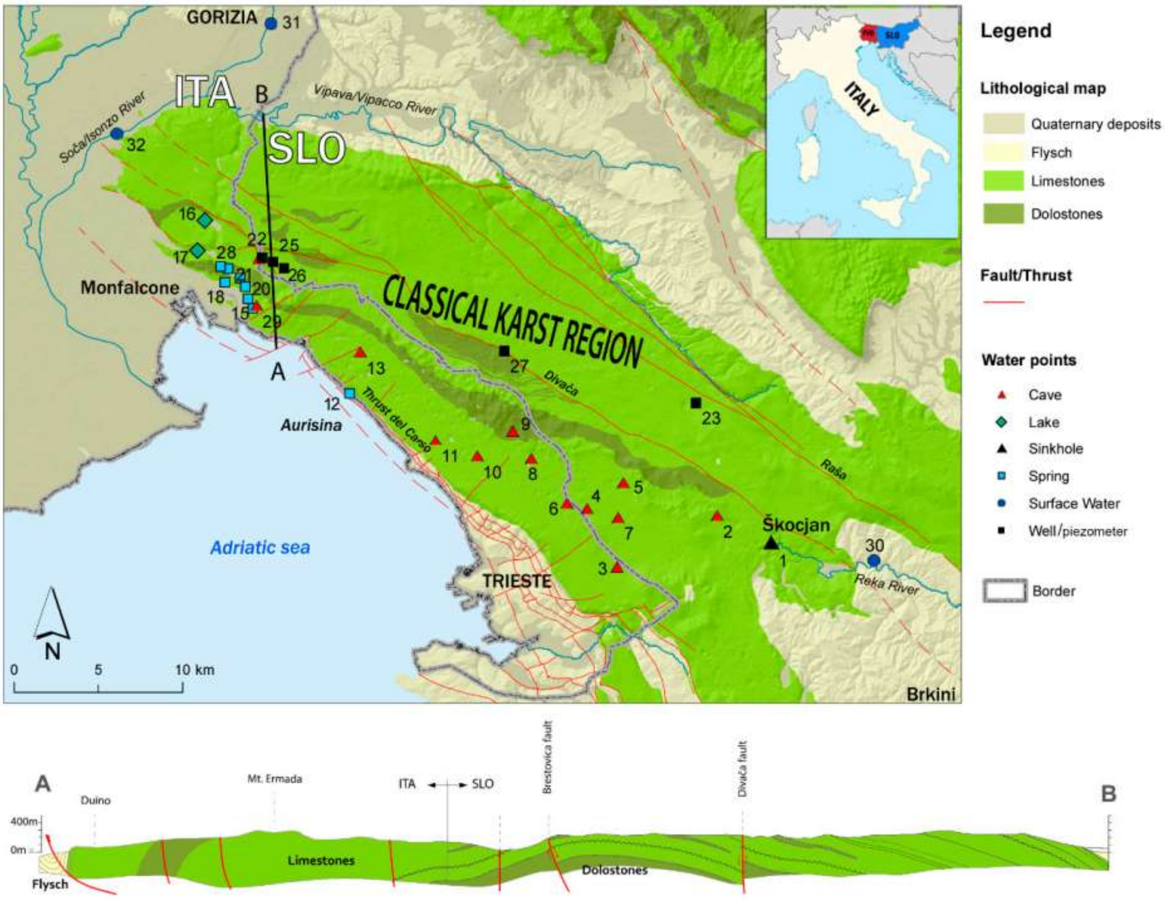

Figure 33: Lithological map of karst area

From the geotectonic point of view, the Classical karst aquifer belongs to External Dinarides as the southwestern part of the Trieste–Komen anticlinorium which is built from larger and smaller folds. The Brestovica anticlinorium is cored with dolomite near the east–west trending Brestovica fault, which is the most important structure in this research area. Important faults having a typical Dinaric orientation (northwest–southeast) in this region are the Raša and Divača faults (Jurkovšek 2008), and the Palmanova–Črni Kal line (Carulli 2011).

10.3 Geomorphology

Due to the dissolution of carbonate rocks that constitute the aquifer, various karst phenomena have developed (barren karst areas, dolinas, caves, deep shafts, etc.). The surface is formed by hills with gentle elevations reaching an average elevation of 250 – 300 m a.s.l. with the top at Trstelj Hill (643 m).

The analyses conducted by Cucchi and Zini (2002) recognize in the structures one of the main controlling factors in the evolution of karst features: a trend in the discontinuities controlled by the Alpine and Dinaric stresses gave rise to a network of fractures from which the main conduits and alignments of dolines formed. The maximum dip of the strata and the main sub-vertical discontinuities represent in fact the preferential directions for conduits and shafts development. The long-lasting exposure of the plateau shaped it into a mature karst.

From a speleogenetical viewpoint, the plateau emerged at least ten million years ago, during one of the phases of the alpine-dinaric orogeny. The genesis of the karst is marked with different phases. According to the nature of voids, the water was primarily stored and transmitted through the matrix. During the Messinian crisis, the circulating groundwaters enlarged the fissures, developing defined pathways as pipes (conduits or caves).

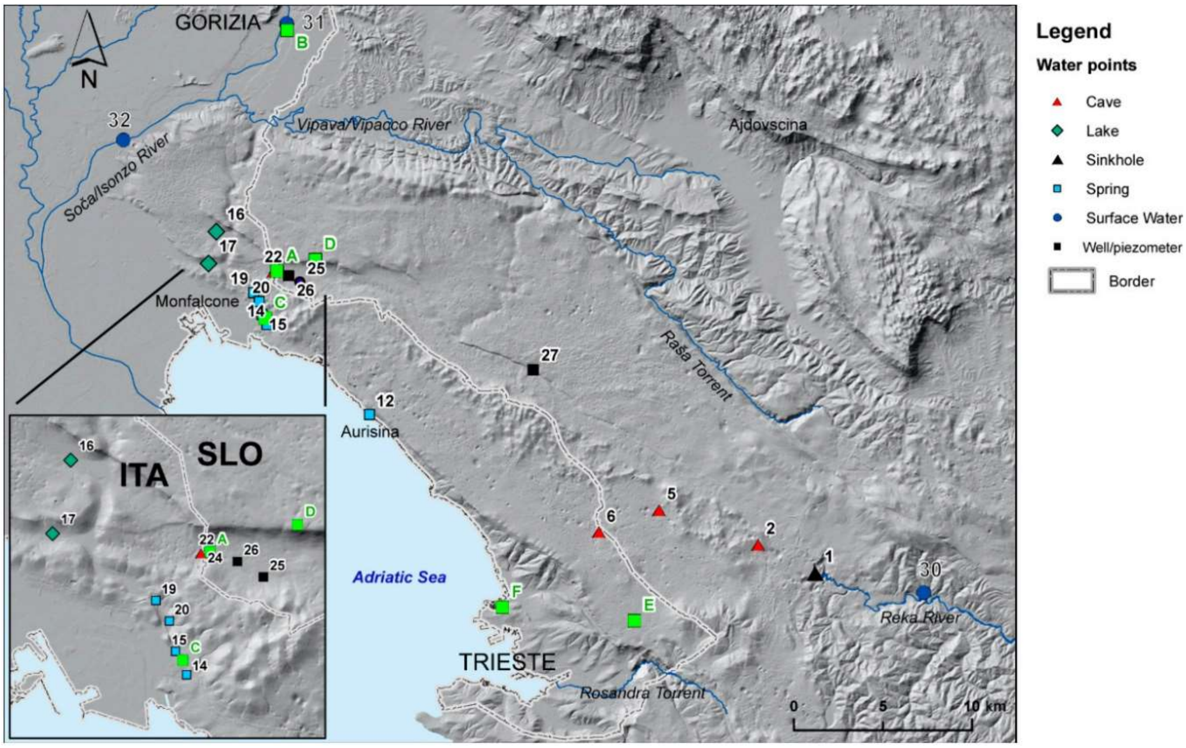

Figure 34: Digital elevation model of the Classical Karst area (Calligaris et al., 2018)

Speleological explorations over the last two centuries have supplied a lot of cave surveys (2000 in Italy and even more in Slovenia). Some caves have been studied in detail from the geological, geomorphological and sedimentological point of view: Lazzaro Jerko Cave, Trebiciano Abyss, Padriciano Cave - in Italy -, Postojna Cave, Kacna Jama Cave, Skocjanske Cave – in Slovenia.

10.4 Climate

The Classical Karst area lies slightly higher than the neighbouring areas. Its edges are hilly and this is the main cause for the climatic isolation and specific climatic conditions of the area. Its proximity to the sea has influence on the climate and the mild sea influences reach the interior part of the area mostly by Brestoviški Dol dry valley.

Partial isolation is the main reason that Karst climate also has some continental characteristics that are mostly featured in cold winters caused by cold air from the northeast. The consequence is strong wind, called "burja". This wind can sometimes bring snow in the area as soon as October and as late as April. Melik mentions that the temperatures are under 0 °C in average 40 days/year (Melik, 1960).

The close to sea position influences the precipitation amount (1,570 mm/year) which differs towards north and northeast. The precipitation is quite equally disposed throughout the year which is typical of continental climate. The Mediterranean climate characteristics can be noticed in October and December precipitation climax. As a continental climate characteristic there is the precipitation climax in May and June. January and February are the driest months, as well as August (Melik, 1960).

Overall Classical Karst area has typical sub Mediterranean climate with some continental characteristics. Typical are quite high summer temperatures (mean monthly July temperature is

21 °C) and cold winters (mean monthly January temperature is 2.5 °C) that are often characterized by the bora cold winds.

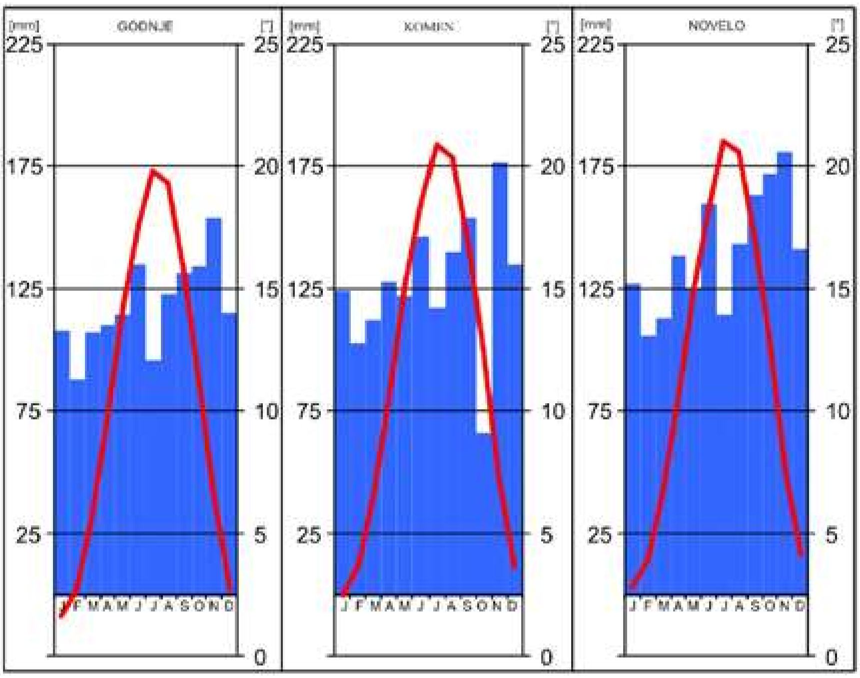

Figure 35: Climatograph of Godnje, Komen and Novelo (1961-1990). Source: Klimatografija Slovenije 1961.-1990.

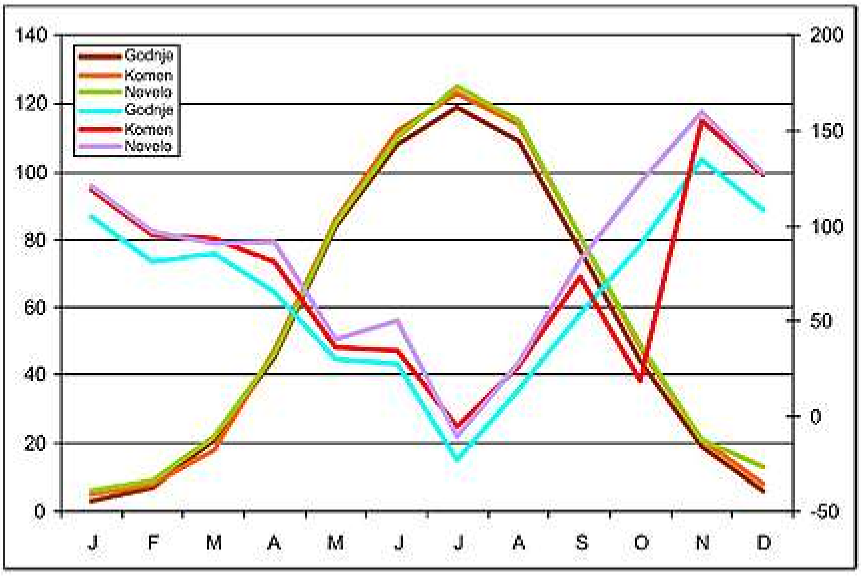

Figure 36: Potential evapotranspiration (according to Thorntwait) in water balance (in mm) Source: Mrak, Repe, 2002.

10.5 Hydrogeology

From a hydrogeological point of view, the Reka-Timavo aquifer system recharge is due to three different contributions: the autogenic recharge resulting from the precipitations on the Karst surface; the allogenic one due to the sinking of the Reka River in the Škocjanske jame sinkhole, and the input coming from the Isonzo alluvial aquifer.

In the Karst area, the first input is the average rainfall contribution considered between 1000 mm/year in the coastal area and 2600 mm/year in the Reka hydrogeologic system, with an effective infiltration of 20.6 m3 /s (Civita et al. 1995).

The second input is from the Reka River. From the spring area, it flows for about 43 km on impermeable rocks in Flysch facies; for the last 7 km, it flows on limestone lithotypes developing an influent character. After 50 km from the spring area, the Reka River totally sinks into the Škocjan sinkhole. It has a mutable discharge with values within the range of 305 m3 /s (in the high water conditions) – 0.18 m3 /s (in low water conditions) with an average value of 8.26 m3 /s (Gabrovšek and Perič, 2006).

The third important water input is occurring in the northwestern sector, in correspondence with the contact between limestones and the Isonzo alluvial aquifer. Its contribution, assumed since the beginning of last century (Timeus 1928), has been later estimated and verified using natural tracers (Mosetti and D'Ambrosi 1963, Gemiti and Licciardello 1977, Doctor et al. 2006) and water hydrogeological balance computation, to 10 m3 /s (Zini et al. 2013).

Waters of the Reka/Timavo River were identified in several caves: B3G Brezno treh generacij, Kačna jama, Jama v Kanjaducah, Brezno v Stršinkni dolini (Slovenia), Abisso di Trebiciano and Pozzo dei Colombi (Italy).

Only during flood periods or heavy rainstorms the groundwaters of the Classical Karst Region aquifer reach the Abisso Massimo, Abisso di Rupingrande, Grotta Skilan, Grotta Lindner, Grotta meravigliosa di Lazzaro Jerko and Grotta Gigante (all in Italy).

The aquifer is also highly karstified at considerable depths: cave divers explored the conduits starting from the Timavo spring reaching more than 80 m b.s.l.; well withdrawals linked to the Slovenian aqueduct network are realized at 55–70 m b.s.l., corresponding with Karst conduits (Urbanc et al. 2012)

The vadose zone of the aquifer at Klariči pumping station is around 20 m thick. With distance from the pumping station to the northeast of the aquifer the unsaturated zone is getting thicker, reaching up to 150 m at Pliskovica (Urbanc *et al.* 2012).

Figure 37: Drinking water pumping station Klariči

The pumping facility Klariči (*Figure 37*) consists of three 70 m deep wells (VB4/79, VB4/80 and VB4/81) with diameters of 400 and 500 mm and a total capacity of 250 L/s. After many pumping tests in the period from 1976 to 1979, a potential estimated capacity of over 1,000 L/s of groundwater was estimated for the Brestovica – Klariči aquifer. Estimated apparent aquifer transmissivity in the area around Klariči pumping station is between 7x10^2 and 8×10^1 m^2/s with an effective porosity between 3–4% (Krivic 1985).

To define the direction of groundwater flow five 50 m deep piezometers were drilled (in 1985) in a 100–120 m radius around the pumping station Klariči. During years 2006–2007 further intensive hydrogeological research took place, where three additional 150 m deep piezometers (Br6, Br7 and Br8) and a new well B10/06 with 600 mm diameter and 80 m depth were drilled (Urbanc *et al.* 2012).

The pumping station Klariči is a part of the Karst water supply system Kraški vodovod Sežana, providing drinking water to five Karst communities (Miren – Kostanjevica, Komen, Sežana, Divača, and Hrpelje – Kozina), and during summer months to the Slovenian Coastal region as well. Usually around 100 L/s are pumped for the Karst area water demand, however, when simultaneously supplying the coastal area, around 200 L/s are extracted (Kristan & Skrinjar 1998).

10.6 Hydrodynamic characteristics of springs

All karst groundwater is drained by the spring system enclosed in a few square kilometers along the coast from the Aurisina spring to Monfalcone town. The main spring is the Timavo, with an average discharge of 29.3 m^3/s, the second is the Sardos (1.9 m^3/s), and the third are all the other smaller springs as Aurisina (0.3 m^3/s), Moschenizze (0.5 m^3/s), Pietrarossa and Sablici lakes (1.2 m^3/s), Monfalcone (0.2 m^3/s), Lisert (1.0 m^3/s), and lastly the coastal springs arising below sea level located between Aurisina and Timavo, having an average estimated discharge of 0,5–1 m3 /s. The Timavo spring is characterized by a large flow fluctuation, between 8 and 155 m^3/s (Gemiti 1984, 1995).

10.7 Data available for the project

Pumping well Klariči VB-4/79			
Data type	Time step	Monitoring period	Time period
GW level	1 hour	9 years	2006 - 2014
Temperature	1 hour	9 years	2006 - 2014
El. conductivity	1 hour	9 years	2006 - 2014

Pumping well Klariči VB-4/80			
Data type	Time step	Monitoring period	Time period
GW level	1 hour	9 years	2006 - 2014
Temperature	1 hour	9 years	2006 - 2014
El. conductivity	1 hour	9 years	2006 - 2014

Pumping well Klariči VB-4/81			
Data type	Time step	Monitoring period	Time period
GW level	1 hour	13 years	2006 - 2018
Temperature	1 hour	13 years	2006 - 2018
El. conductivity	1 hour	13 years	2006 - 2018

Observation well Klariči B-9			
Data type	Time step	Monitoring period	Time period
GW level	1 hour	13 years	2006 - 2018
Temperature	1 hour	13 years	2006 - 2018

El. conductivity	1 hour	13 years	2006 - 2018

Pumping well Klariči BR-7			
Data type	Time step	Monitoring period	Time period
GW level	1 hour	11 years	2008 - 2018
Temperature	1 hour	11 years	2008 - 2018
El. conductivity	1 hour	11 years	2008 - 2018

10.8 Summary

Pilot name	**CLASSICAL KARST AQUIFER**		
Country	Slovenia / Italy	EU-region	Mountain areas
Area (km^2)	750	Lithology	Limestone & dolomite
The Classical Karst is a transboundary area s of approx. 750 km^2 shared between Italy and Slovenia. It is the most famous karst area in the world, where the word karst was used for the first time. Classical Karst area is built primarily of intensive limestones and dolomites of Cretaceous and Paleogene age.	 All karst groundwater is drained by the Timavo spring system enclosed in a few square kilometers along the coast.		
Monitored objects	Pumping and observation wells; springs		
Monitored data	GW level, temperature, EC		
Contact person	Janko Urbanc (janko.urbanc@geo-zs.si)		

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11 AUSTRIA: WALDBACHURSPRUNG SPRING

11.1 Overview

The Dachstein massif represents one of the largest karst plateaus in Austria, covering an area of 40 km in length by 20 km in width and reaching an altitude of 2995 m above sea level (*Figure 38*). This region, the site of the prehistoric salt mine of Hallstatt, is a UNESCO World Heritage Site.

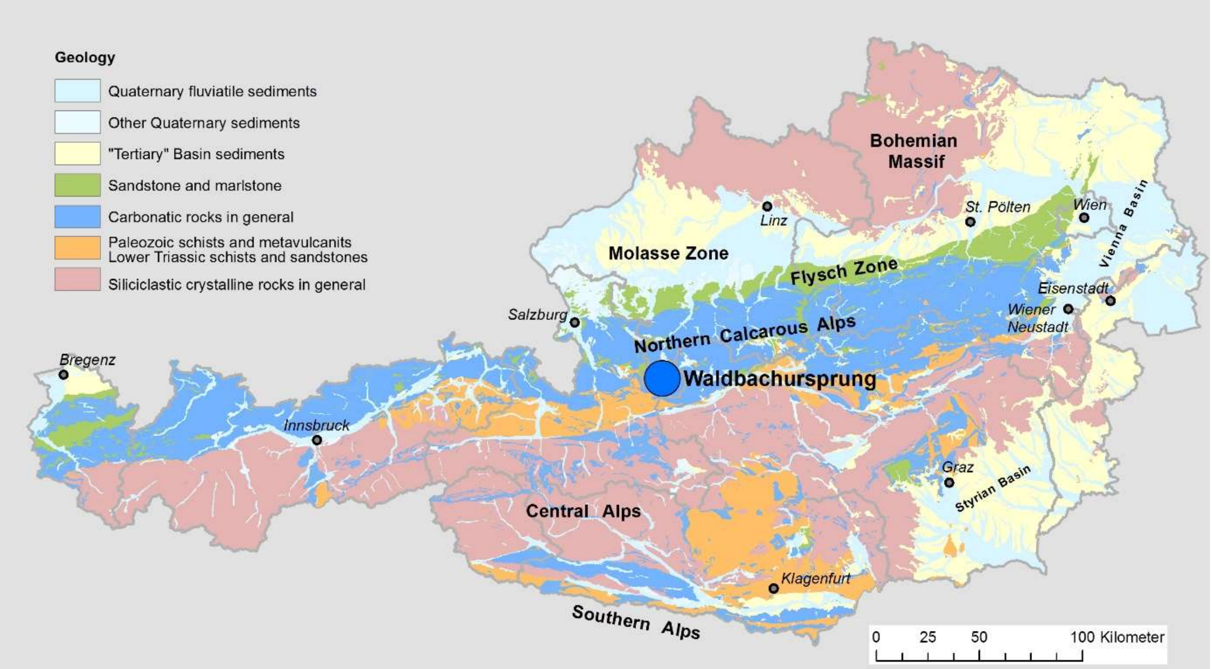


Figure 38: Location of the Waldbachursprung in Austria.

11.2 Geology

The main drainage of the Dachstein massif takes place in the very thick (approximately 1000 m) Dachstein limestone which slopes down towards the north and is highly karstified (*Figure 39*). It is underlain by dolomites with a thickness of up to 1000 m which act as a barrier that declines towards the north. In the southern extent, outcrops of the underlying dolomites are widespread. The dolomites themselves are underlain by a barrier of sandy/slaty rocks of the Permoskythian era.

Towards the north

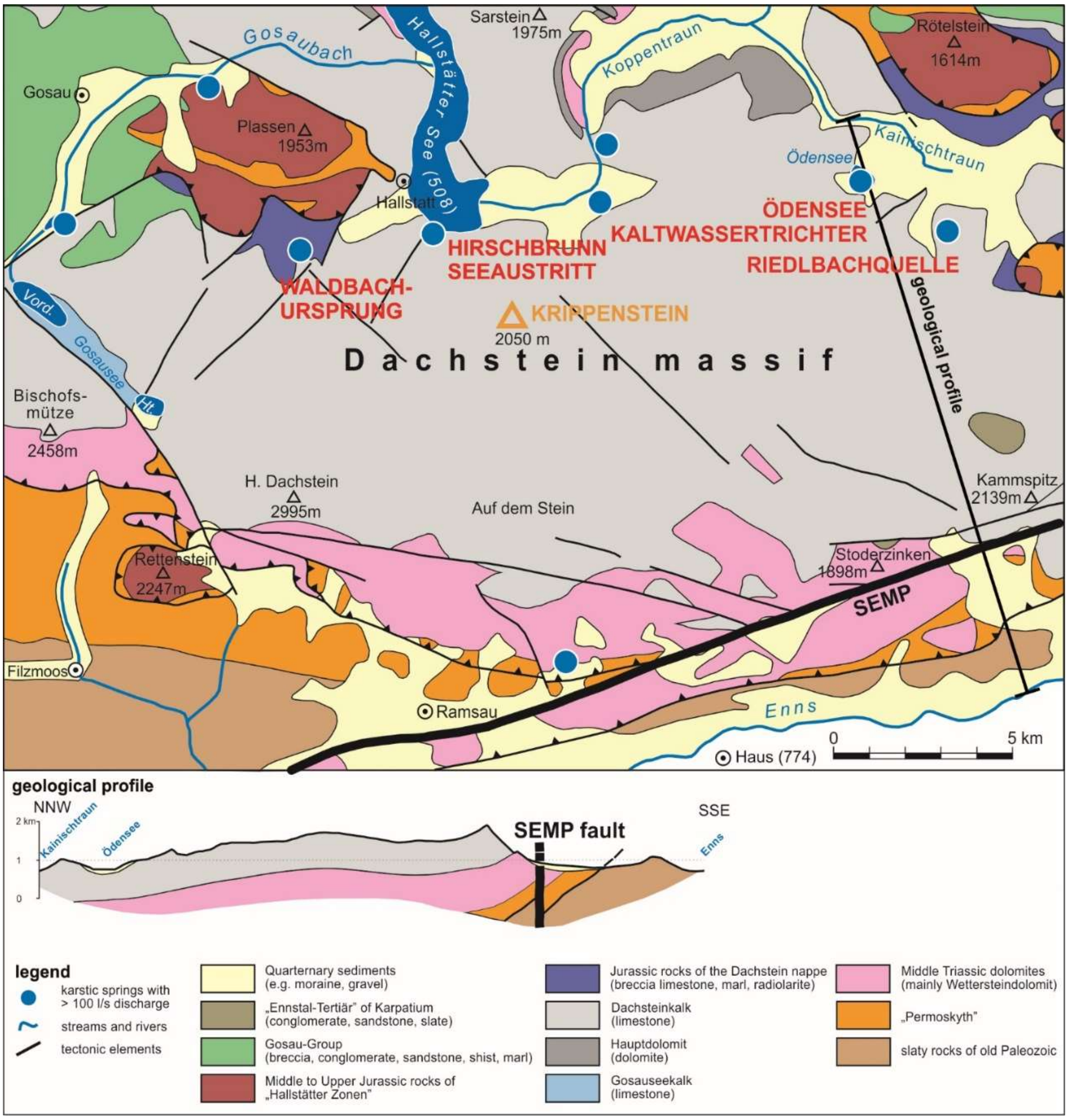


Figure 39: Dachstein massif with chosen springs (Waldbachursprung, Hirschbrunn-Seeaustritt, Ödensee-Kaltwassertricher and Riedlbachquelle) and precipitation monitoring station (Krippenstein) (modified after Schubert, 2000).

11.3 Climate

The annual precipitation of the Dachstein region is approximately 2500 mm. *Figure 40* provides an overview of daily precipitation including snow, and air temperature, for the monitoring station Krippenstein located at an elevation of 2050 m asl. (*Figure 39* for location).

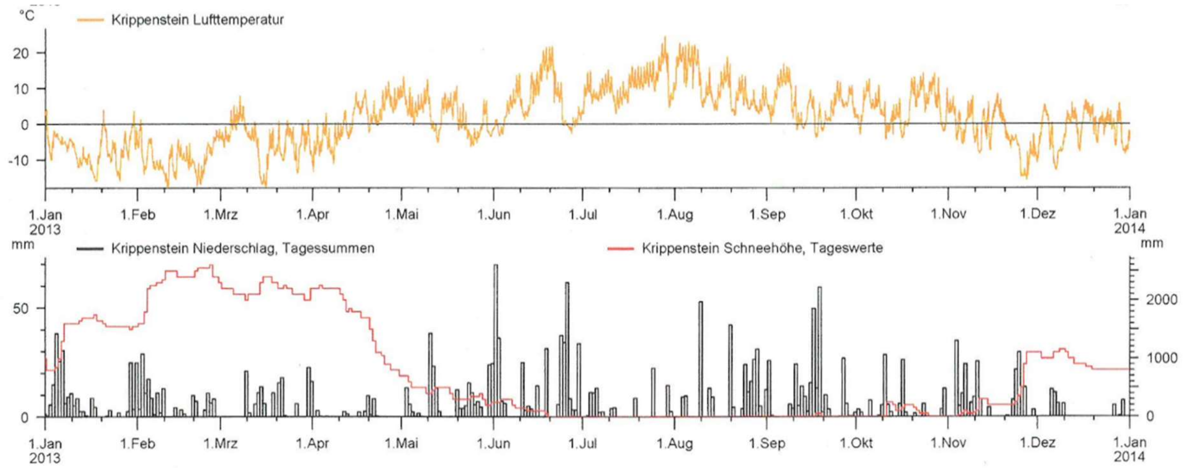


Figure 40: Precipitation, snow level, and air temperature of Krippenstein monitoring station (year 2013) (Völkl & Eybl, 2019).

11.4 Hydrogeology

There have been many tracer tests in the Dachstein massif. These investigations have been an important contribution to the progress of tracer techniques. Both Lycopodium spores and fluorescent dye tracers have been used. In the Dachstein region Lycopodium spores were used in 1953 by MAYR (1956). He injected tracer into a swallow hole on the shore of the lake Hinterer Gosausee (point F2 in *Figure 40*) and found connections to the karst spring Waldbachursprung (point E1) in the northeast and to the karst springs in the southern Gosau valley (point F4) in the north-west. In times of a high groundwater level this swallow hole acts as spring.

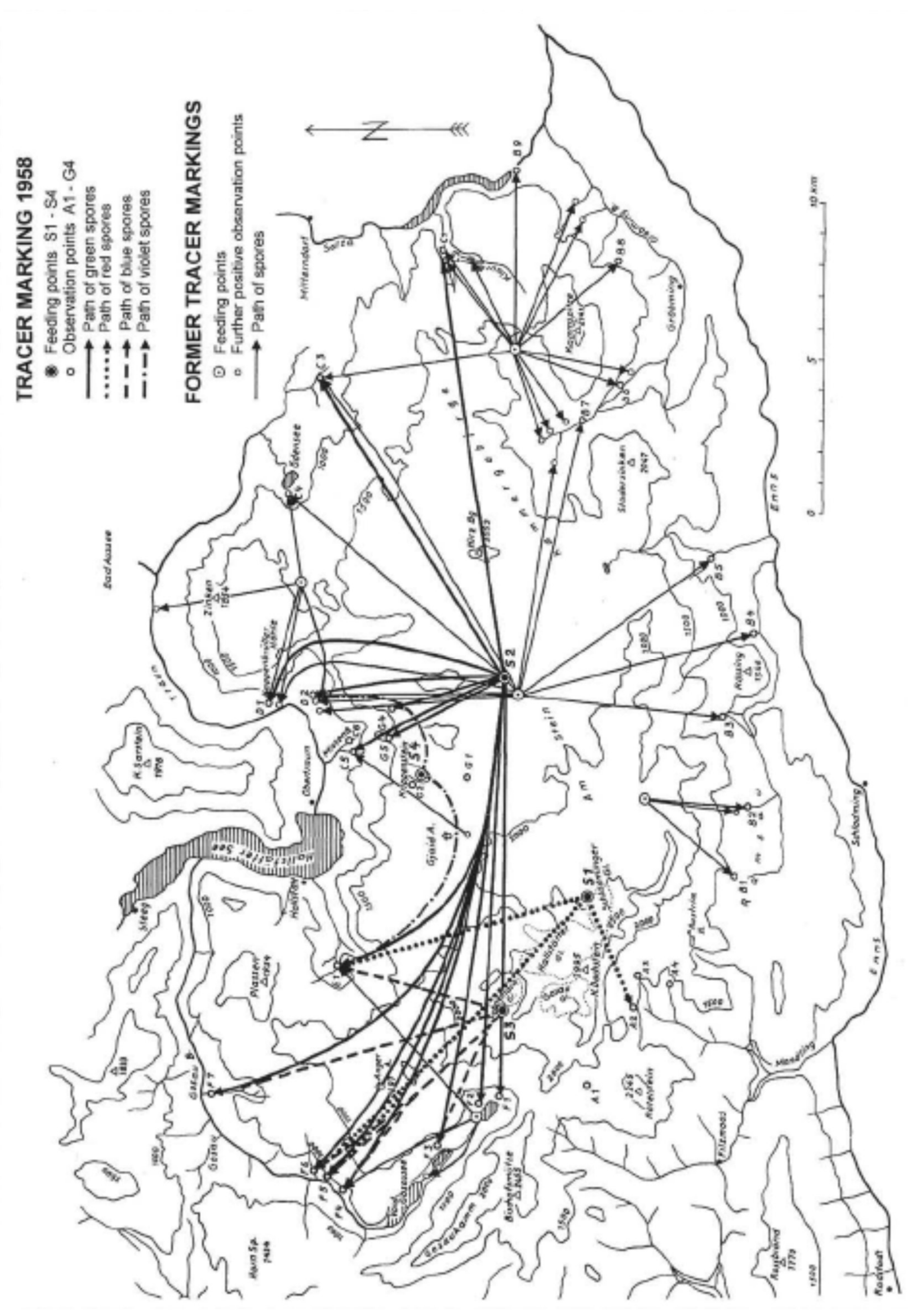


Figure 41: Results of the spore tracer tests in 1958 and earlier (MAURIN and ZOTL, 1959). The spore tracer tests led to the assumption of a radial karst discharge.

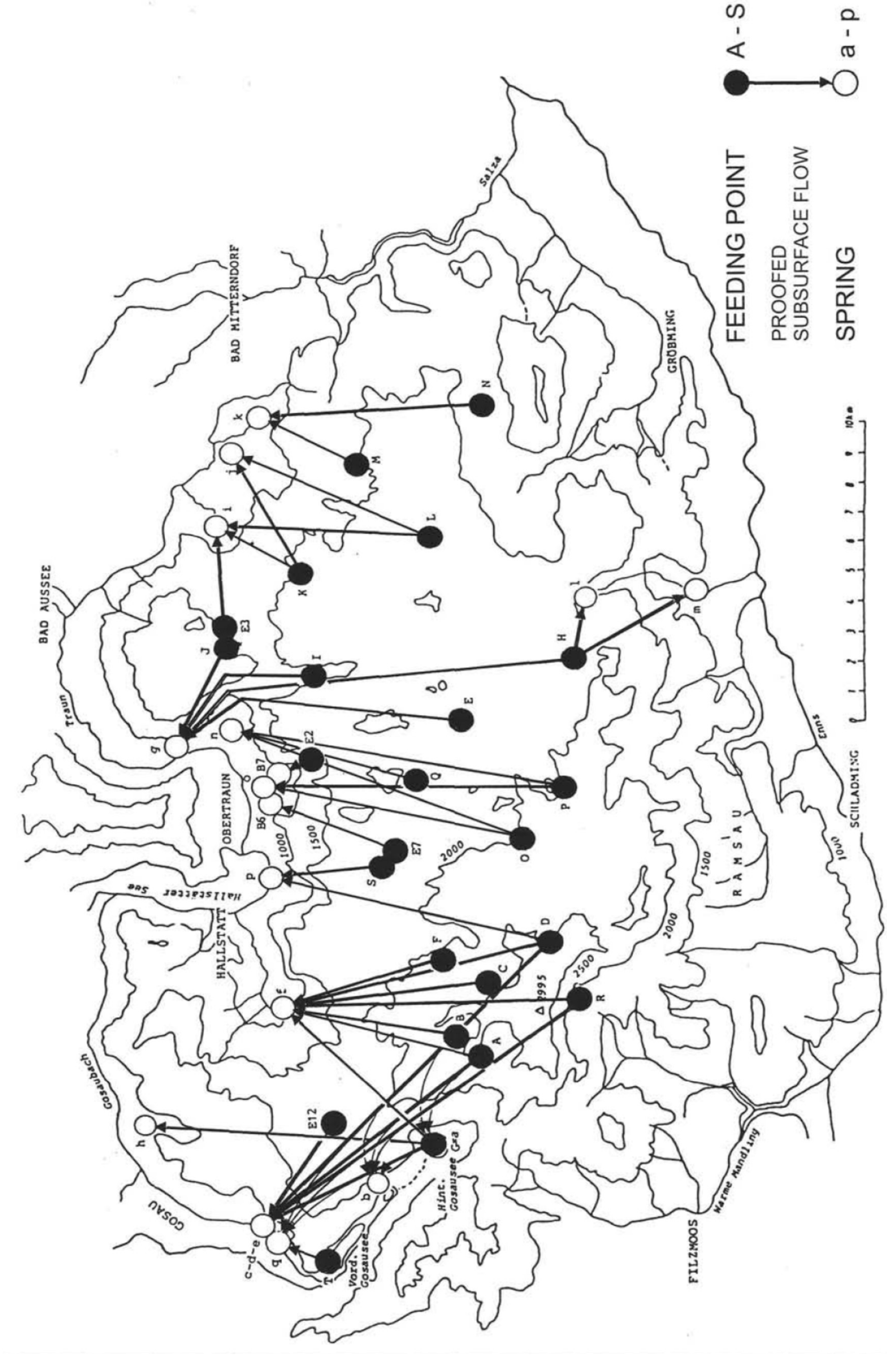
Due to a new method of dying Lycopodium spores in different colors (DECHANT, 1959), it became possible to apply Lycopodium spores simultaneously to several places within one area (Schubert, 2000). In 1956 and 1958, extensive spore tracer investigations were carried out in the whole Dachstein massif (MAURIN and ZÖTL, 1959). The results of these tracer tests led to the conclusion that the subsurface drainage of the Dachstein massif runs from the central region radially in all directions (Figure 41).

Extensive fluorescent dye tracer tests were carried out in 1984, 1985, and 1986, by BAUER (1989). They showed that the subsurface drainage of the Dachstein massif is essentially northwards (*Figure 42*) and not, as MAURIN and ZOTL (1959) suggested, radial. A dye tracer was only found in springs on the southern side of the Dachstein massif in two cases (points I and m in Figure 42). BAUER (1989) assumed there is a subsurface drainage divide located in the southernmost part of the Dachstein massif. In his opinion, many of the connections found by spore tracer tests were not a result of subsurface runoff but a result of sample contamination. He suggested connections were only proven if the tracer concentrations in spring water produced a tracer breakthrough curve.

In 1990, the Federal Environment Agency (Vienna) carried out two further dye tracer tests in the western Dachstein region (HERLICSKA and HOBIGER, 1991). The aim of these investigations was to explore the recharge area of karst springs located in the southern Gosau valley (points c, d, e, and q in *Figure 41*) and west of Hallstatt (point f) in detail. It became apparent that the recharge areas of these two spring groups overlap strongly. The velocities during high flow conditions were considerably higher than during low flow conditions.

An extensive spring monitoring program was conducted by the Federal Environment Agency in the years 1991 to 1994, the so-called "Karst-Water Dachstein" project (HERLICSKA, 1994; SCHEIDLEDER, 2000). In this context, supplementary geological mapping was carried out by the Geological Survey of Austria (MANDL, 2000). Based on the new hydrographic, hydrochemical, isotopic, and geological data, the understanding of the subsurface runoff in the Dachstein massif was considerably improved (TRIMBORN et al. 2000; SCHUBERT, 2000). The results are summarized below.

The Dachstein massif consists of a generally northward dipping Triassic carbonate sequence, which belongs to the Dachstein nappe. The basal aquiclude of these carbonates comprises Permoskythian and Early Paleozoic slaty-siliciclastic strata of different tectonic origin. The upper part of the carbonate sequence consists of up to 1000 m thick, strongly-karstified Norian Dachstein Limestone. This limestone forms the main aquifer in the Dachstein region; with rapid subsurface runoff toward the big karst springs in the north (from here on called “the northern springs”). The Waldbachursprung is the biggest karst spring of the Dachstein region. The lower part of the carbonate sequence comprises a 1000 m thick, Anisian to Early Carnian dolomite succession (mainly Wetterstein Dolomite). Relative to the overlying Dachstein Limestone, the dolomite succession forms an aquitard. In the south of the Dachstein Massif, in the Enns valley, the dolomites crop out extensively. Here, several small springs rise within the base of the dolomites (From here on called “the southern springs”).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Gosaubach
GOSAU
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Figure 42: Results of the Dye tracer tests in 1984, 1985, and 1986 (BAUER, 1989). Based on a critical evaluation, BAUER (1989) infers a predominantly northwards subsurface drainage within the Dachstein massif, which is in contrast to MAURIN and ZÖTL (1959).

In the areas of the Plassen and Rettenstein mountains, as well as in the surroundings of Bad Mitterndorf, tectonic blocks consisting of a heterogeneous sediment sequence occur on the Dachstein nappe. This uppermost tectonic unit is called the Hallstatt zone. For example, the Permian evaporites of the salt mine in Hallstatt (Haselgebirge) belong to it. The springs rising within these tectonic blocks have mostly local recharge areas. As a consequence of the heterogeneous bedrocks, they have variable chemistries.

In the following, the characteristics of the northern springs (limestone type) and the southern springs (dolomite type) are considered. The northern springs are characterized by high Ca^{2+}/Mg^{2+}-ratios (indicating calcareous inflow areas) and strongly varying discharges and $\delta^{18}0$-concentrations (indicating rapid subsurface runoff). Most hydrographs of the northern springs indicate a runoff composition of 21 to 28 % of a younger component water (mean residence time <0.1 years) and 62 to 65% of an older water (mean residence time 3 years).

As the dye tracer tests show, the subsurface drainage of the Dachstein massif generally flows in a northerly direction (*Figure 43*). However, in the western Dachstein massif the subsurface runoff is split into the springs in the southern Gosau valley and into the spring district of the Waldbachursprung. This splitting is caused by the damming effect of the deep-drawing Permian and Early Triassic siliciclastic strata of the Hallstatt zone in the surroundings of Plassen.

The southern springs of the Dachstein massif are dominated by a dolomite-rich recharge area. This is indicated by the relatively low Ca^{2+}/Mg^{2+}-ratios and by the relatively low and constant outflows, as well as low variations in $\delta^{18}0$-concentrations. The Ca^{2+}/Mg^{2+}-ratios lie between 1.6 and 3.6 with a few exceptions, which rise on the contact between the Dachstein limestone and dolomite. The relatively constant $\delta^{18}0$-concentrations suggest high residence times. The longer $\delta^{18}0$-hydrographs of the southern springs suggest an outflow composition of 3 to 14 % of younger component water (mean residence time 0.2 to 0.4 years) and 86 to 94% of an older component (3 to 6 years). Springs with a dolomite-dominated recharge area are, as a rule, characterized by a more constant outflow and higher residence time, due to the high fracture porosity and storage capacity of dolomite.

With regard to sulphate, the southern springs can be divided into a western group with high $S0_4^{2-}$concentrations and an eastern group with low ones. Whereas in the southwest of the Dachstein massif the groundwater of the dolomite sequence has contact with evaporites belonging to the aquiclude, this is not the case in the east.

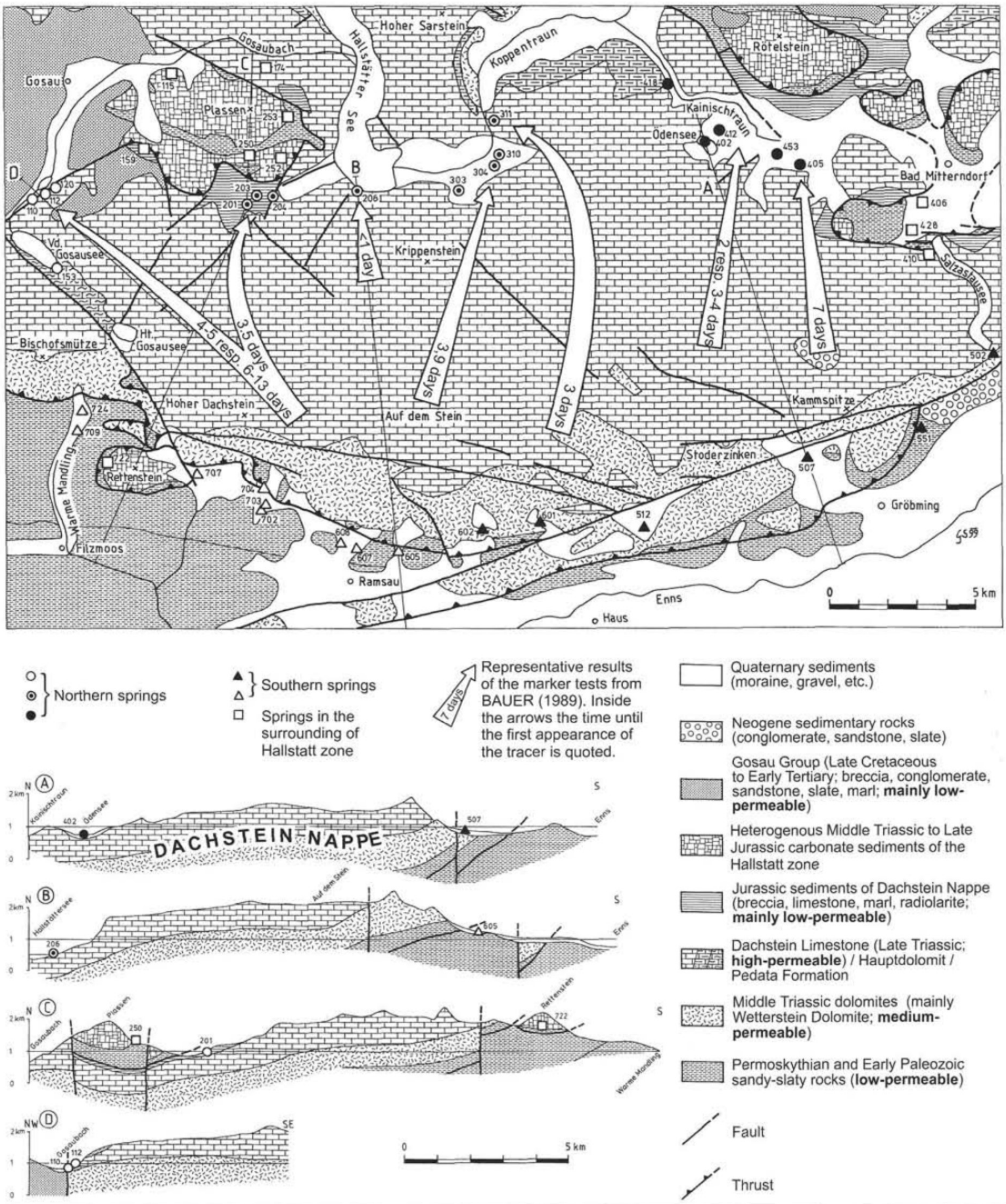


Figure 43: Hydrogeological outline map and cross sections of the Dachstein massif (SCHUBERT, 2000; geology after MANDL, 2000 and TOLLMANN, 1960).

11.5 Hydrodynamic characteristics of the springs

Figure 44 provides an overview of the discharge of the Waldbachursprung, Riedlbachquelle, Ödensee-Kaltwassertrichter and Hirschbrunn-Seeaustritt springs in relation to precipitation, snow level and air temperature.

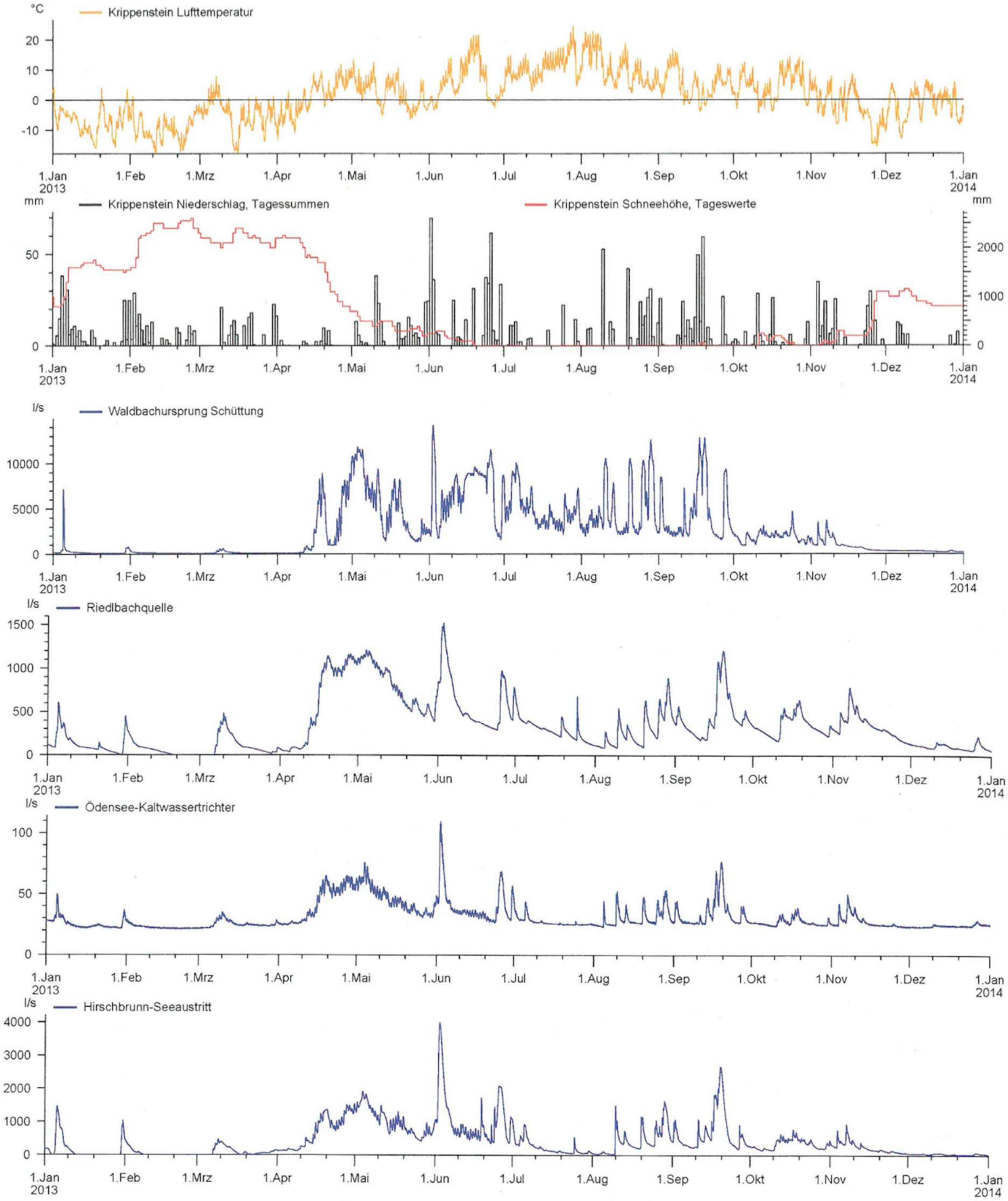


Figure 44: Precipitation, snow level, and air temperature of the Krippenstein monitoring station (year 2013) and discharge of spring monitoring stations at Waldbachursprung,

Riedlbachquelle, Ödensee-Kaltwassertrichter, Hirschbrunn Seeaustritt (year 2013) (Völkl & Eybl, 2019)

Figure 45: Waldbachursprung (picture: Eybl, BMNT, Abteilung I/4 Wasserhaushalt).

Figure 46: Hirschbrunn-Seeaustritt (picture: Eybl, BMNT, Abteilung I/4 Wasserhaushalt).

Figure 47: Ödensee-Kaltwassertrichter (picture: Eybl, BMNT, Abteilung I/4 Wasserhaushalt).

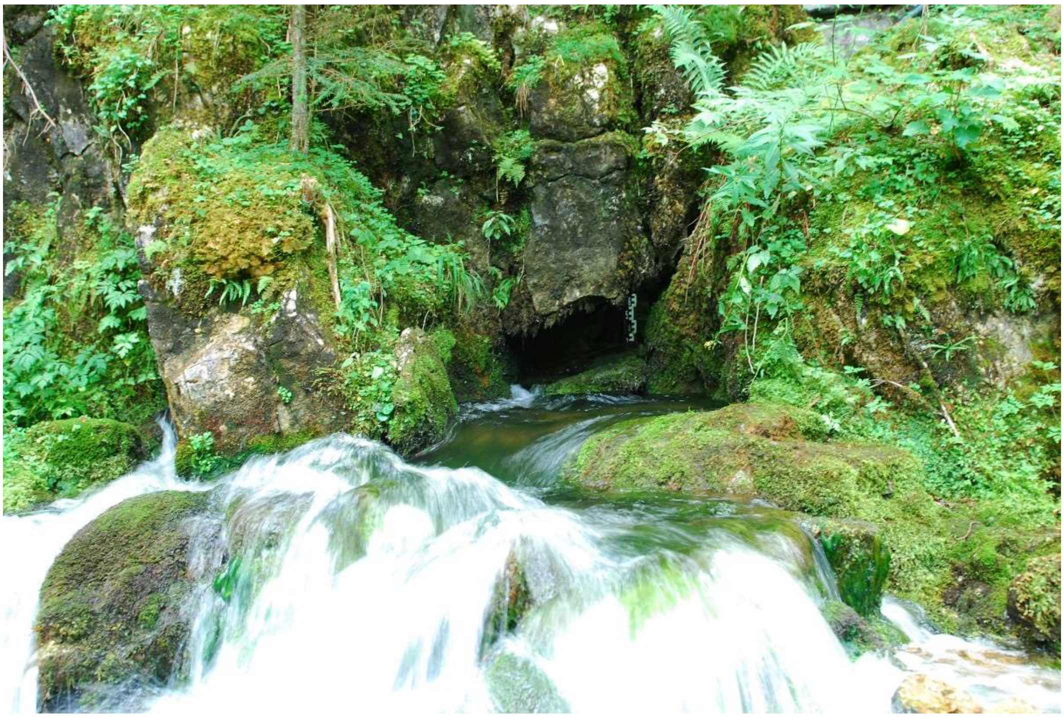


Figure 48: Riedlbachquelle (picture: Eybl, BMNT, Abteilung I/4 Wasserhaushalt).

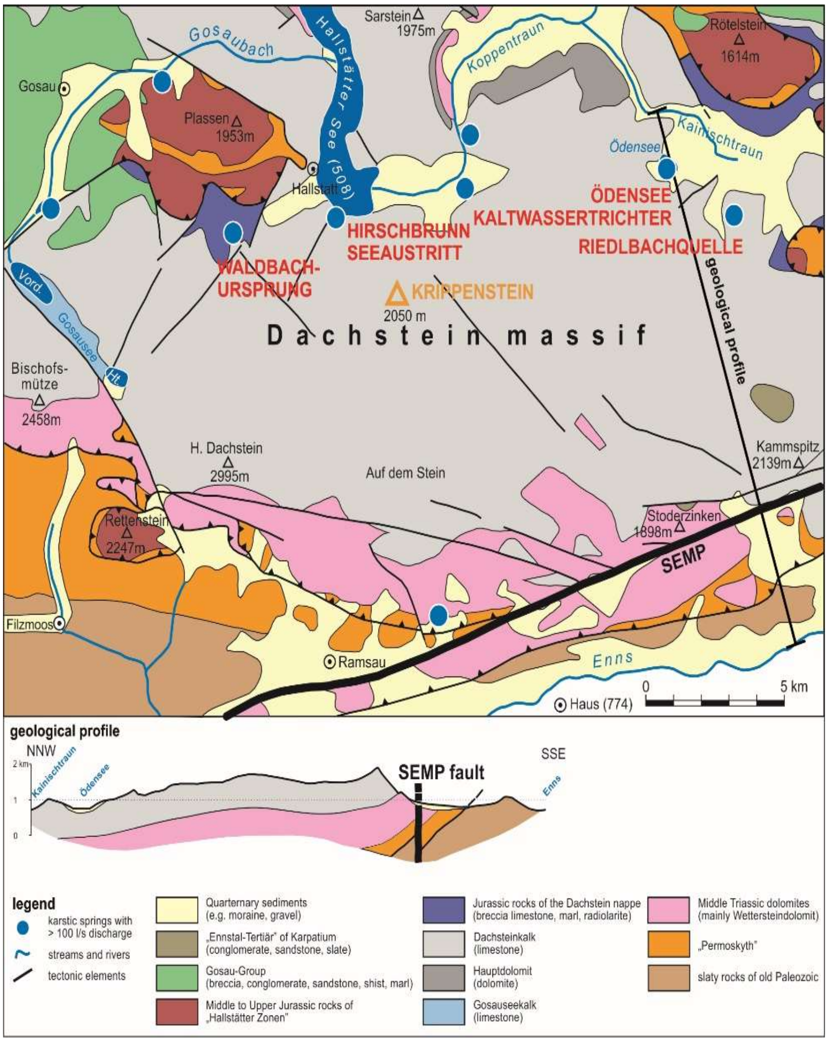
11.6 Data available for the project

Data can be provided for the Waldbachursprung, Riedlbachquelle, Ödensee-Kaltwassertrichter and Hirschbrunn-Seeaustritt springs. Furthermore it is possible to contribute precipitation data.

Name	Parameter	Time period
Krippenstein	Precipitation (mm/d)	1/1995-8/2019: daily value; 15 min: 2013
Waldbachursprung	EC (µS/cm), Q (l/s), T (°C)	2/1996-12/2018:daily values; 15 min: 2013
Riedlbachquelle	EC (µS/cm), Q (l/s), T (°C)	1/2008-7/2018: daily values; 15 min: 2013
Ödensee-Kaltwassertrichter	EC (µS/cm), Q (l/s), T (°C)	7/1998-1/2019: daily values; 15 min: 2013
Hirschbrunn-Seeaustritt	EC (µS/cm), Q (l/s), T (°C); Turbidity only in 2013	5/2008-1/2019: daily values; 15 min: 2013,

11.7 Summary

Pilot name	**Waldbachursprung spring**		
Country	Austria	EU-region	Alpine
Area (km^2)	40x20	Lithology	Limestone

<table>
<tr>
<td>Short description:
The Dachstein massif consists of a northward dipping Triassic carbonate sequence, which belongs to the Dachstein nappe. The basal aquiclude of these carbonates comprises Permoskythian and Early Paleozoic slaty-siliciclastic strata of different tectonic origin. The upper part of the carbonate sequence consists of up to 1000 m thick, strongly-karstified Norian Dachstein Limestone. This limestone forms the main aquifer in the Dachstein region; with rapid subsurface runoff toward the big karst springs in the north. A representative example is the Waldbachursprung because it is the biggest karst spring of the Dachstein region.</td>
<td>


</td>
</tr>
<tr>
<td>Monitored objects</td>
<td>Four springs (Waldbachursprung, Riedlbachquelle, Ödensee-Kaltwassertrichter, Hirschbrunn-Seeaustritt) and a precipitation monitoring station (Krippenstein)</td>
</tr>
<tr>
<td>Monitored data</td>
<td>Discharge, temperature, electrical conductivity, turbidity</td>
</tr>
<tr>
<td>Contact person</td>
<td>Daniel Elster (daniel.elster@geologie.ac.at)</td>
</tr>
</table>

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12 HUNGARY: NAGY-TOHONYA SPRING

12.1 Overview

The Nagy-Tohonya catchment belongs to the Aggtelek karst region. The Aggetelek Karst is the Hungarian part of the Gömör–Tornai Karst unit, which is divided into two parts: Slovakian and Hungarian. The site extends within the Borsod-Abaúj-Zemplén county in Hungary and the Rožňava county and the Košice county on the Slovakian side. Usually the Hungarian part is mentioned as "the Aggetelek Karst". The two sides are similar in their geological, hydrogeological and geographical characteristics. It is considered to be one of the most important transboundary groundwater bodies located between Hungary and Slovakia. The Aggtelek Karst includes the Aggtelek Mountains and the Alsó-hegy, known as Lower Hill. Together these represent the Hungarian part of the Gömör-Tornai Karst. The Slovakian part of the Gömör-Tornai karst is the South-Slovak Karst. The geographic position of the Aggtelek Karst is indicated in *Figure 49*.

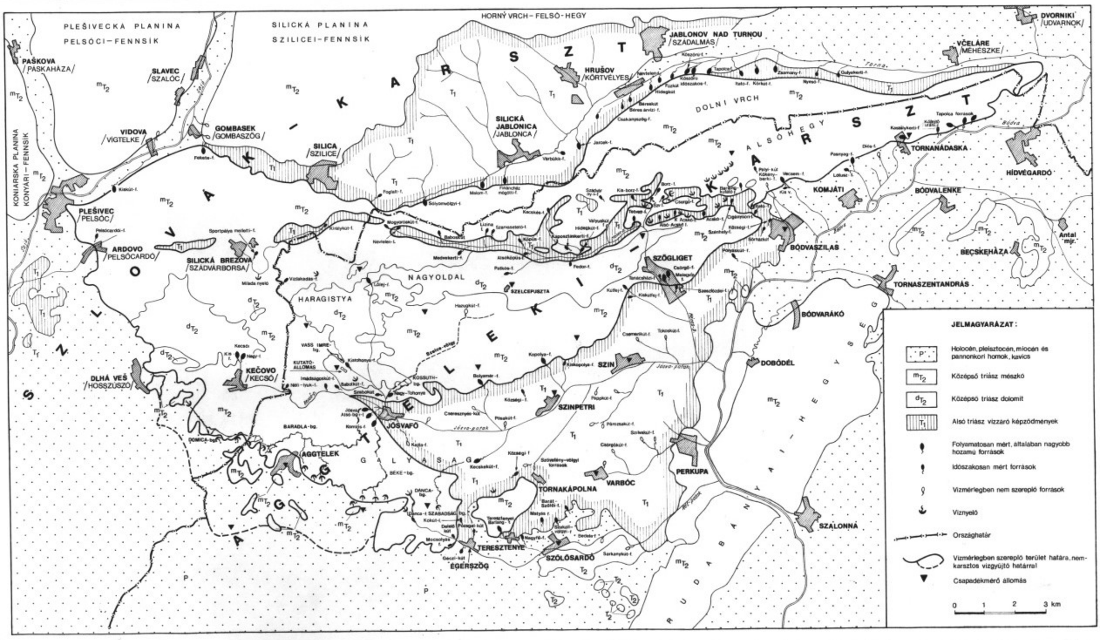


Figure 49 : The Aggtelek Karst (Maucha et al. 2000)

12.2 Geology

The Aggtelek Hills cover an area of 202 km^2. They are situated in the Northern part of Hungary, being in contact with the South-Slovak Karst through the state border. The area belongs to the Southern Limestone Range of the Carpathians.

The Hungarian side consists of East-West orientated limestone plateaus, with an elevation of 400-600 metres above sea level. Between them deep valleys are incised, to an elevation of 200-260 metres. On the other side of the state border the highest plateaus of the Slovak Karst have an elevation up to 800 metres, and toward the North the mountain range is even higher.

The main mass of the mountains comprises sedimentary rocks of Triassic age. The Lower-Triassic layers are mainly aquicludes: clay-slates and sandstones, covering an area of 62 km^2. Above them the Middle- and Upper-Triassic sediments consist of well karstified limestones and dolomites with a surface area of 105 km^2. Miocene age sand and gravel layers can be found in a much smaller extent in the southern part of the area (Maucha et al. 2000). The Pliocene sediments (clay, sand, gravel) cover a larger area, approximately 35 km^2. The Pleistocene is represented by the 0.2–1.0 m thick clayey soil on the top of the plateaus. In the valleys the Holocene alluvium consists of gravel and sand.

The Aggtelek Hills can be described by assuming the existence of overthrust folds. Four different overfields can be distinguished. The plateaus are situated above pseudo synclines, where they remained untouched between the uplifted tectonic zones, which brought the Lower-Triassic layers to the surface. In some places outcrops of Permian layers can be observed below the Lower-Triassic sediments. Figure 50 shows the geological structure of the Aggtelek Karst.

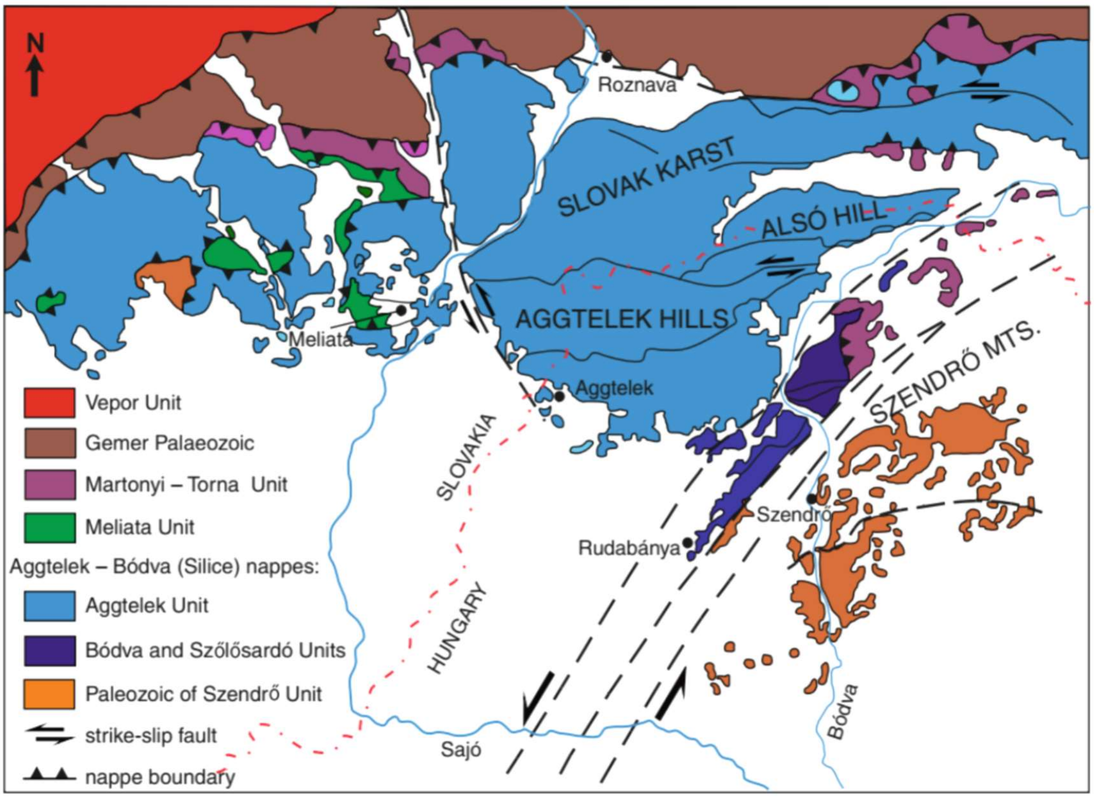


Figure 50: Geology of the Aggtelek Karst

12.3 Climate

The Aggetelek Karst area is situated in the continental climate region. According to the meteorological surveys carried out in the last 35 years the average temperature is 8.8 °C. The average annual temperature varies between 8.5°C and 9.1°C. The hottest month is July with an average monthly temperature of 19.2°C, the coldest is January (-2.8°C). The daily recorded temperature ranged from +28.4 °C to -18.9 °C during the study period, between 1958 and 2008.

The mean annual precipitation is 620 mm according to the Hungarian Meteorological Service. The driest period of the year is in the first three months (January, February and March), the average monthly precipitation is around 30 mm during this period. The rest of the year is wetter, especially during the summer period. The maximum amount of precipitation is in June and July, when the precipitation exceeds 80 mm.

12.4 Hydrogeology

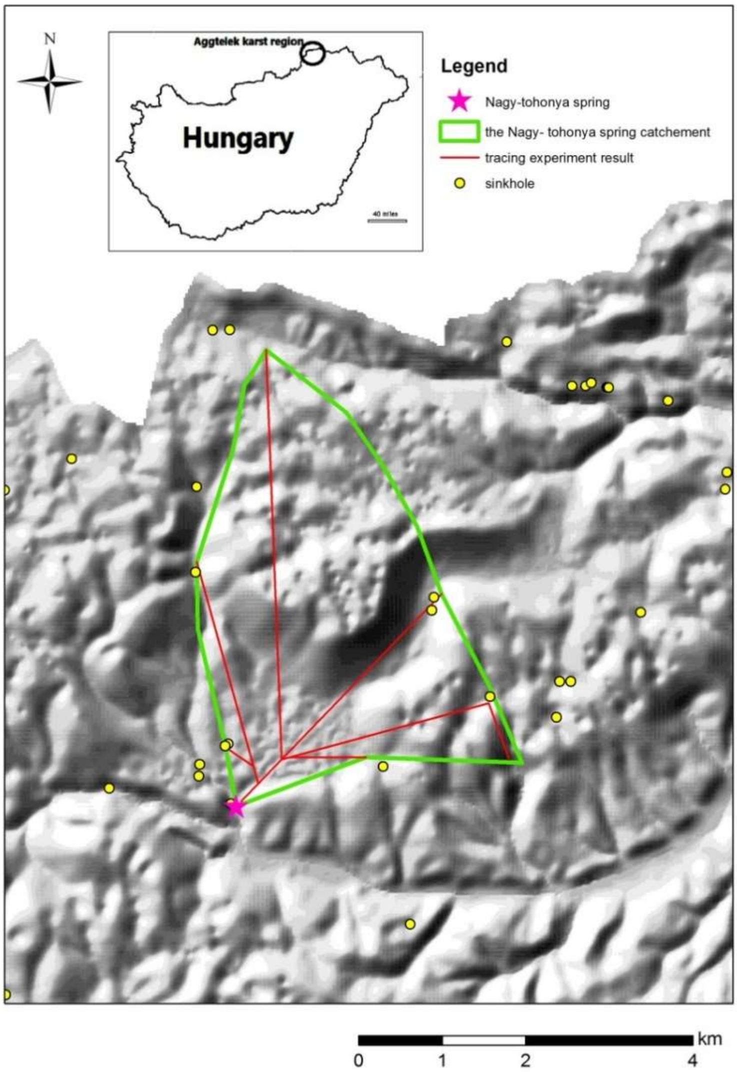
Much of the precipitation is infiltrated on the doline-covered plateaus and transported to the springs by the network of the fracture-system. In the Southern part of the region, where non-karstic (impermeable) areas occur in the spring catchment areas (e.g. Jósva and Komlós springs), small, intermittent water-courses, developed from surface runoff, feed the springs through well-developed swallow-holes. Most important springs of the piedmont have some thermal component. The thickness of the carboniferous layers is at least 1000 metres, and so deeper heated water also supplies the springs.

The dissolution residuum of the Middle- and Upper-Triassic limestones in the Aggtelek Karst is relatively small, a few percent, so they can be classified as highly soluble rocks. Every 10 000 m^3 of water flowing out from the springs contains the equivalent of approximately 1 m^3 of solid rock. As a result, all the larger springs are fed by caves. The distribution of cave passage directions proves that, beside the main E-W directed structural lines, the secondary fracture-system (with a 45 degree of inclination to the main system) also has a role in conducting groundwater to the springs. There are more than 50 springs across the whole karst area (involving the Hungarian and Slovakian regions).

12.5 Data available for the project

Nagy-Tohonya spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	30 years	1964-1993
Electrical conductivity	1 week	30 years	1964-1993
Temperature	1 week	30 years	1964-1993

12.6 Summary

Pilot name	**Nagy-Tohonya Spring**		
Country	Hungary	EU-region	Mountain areas
Area (km^2)	12,5	Lithology	Limestones
Short description: The Nagy-Tohonya spring catchment belongs to the Aggtelek Karst area in North-Eastern Hungary. The aquifer comprises Triasic Limestones. The catchment area is around 12.5 km^2. The spring discharge varies between 0.1 and 1.14 m^3/s.			
Monitored objects	Spring		
Monitored data	Discharge, temperature, EC		
Contact person	Dr. Nóra Edit Gál (gal.nora@mbfsz.gov.hu), Andrea Jordánné Szűcs (andrea.szucs@mbfsz.gov.hu)		

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13 SPAIN: LA FÁJARA SPRING

13.1 Overview

The la Fájara spring is located in the South of Spain, in the autonomous region of Andalucía, in the province of Málaga, 34 km to the North-East of the city of Málaga. The source is located in the area of the Sierra Tejeda-Sierra Almijara-Sierra de los Guájares Triassic marble karst (*Figure 51*). The spring of la Fájara drains the south-western part of Sierra Tejeda (*Figure 52*) and the area is characterised by a pronounced relief but with an absence of typical karst dissolution morphology. La Fájara is a famous site because it is the origin of the local Bermuza river and because 30 m above the spring the entrance to la Fájara cave forms a trop plein (overflow) after heavy rainfall events.

The la Fájara spring is formed at the contact between Triassic marbles and Paleozoic schists, at an altitude of 470 m above sea level. The catchment area is estimated to be about 17 km^2. The spring data have been provided by the Centro de Hidrogeología de la Universidad de Málaga (Spain), the director is Professor Bartolomé Andreo.

Figure 51: The geographic location of the "la Fajara" spring (blue solid dot) in Southern Spain. The underground catchment area is the blue polygon in the figure.

13.2 Geology

The catchment area of the "La Fájara" spring is mainly within the Triassic carbonate marbles which unconformably overlie Paleozoic schists which form the impermeable base to the aquifer. From a geological point of view the aquifer is inside the Internal Zone of the Betic Cordillera as part of the Apujarride Complex (Sanz de Galdeano et al., 2019). These materials are affected by regional Alpine metamorphism. The lithology is marble (from limestones and dolostones) of Triassic age. The general structure of the area (*Figure 52*) are large folds of approximately E-W orientation. The catchment of la Fájara spring forms one flank of an anticline (*Figure 52*).

13.3 Geomorphology

Exokarst

The landscape of the catchment basin presents few forms of dissolution like karren and closed depressions (dolines). However there are many potholes developend at the intersection of fractures.

Endokarst

A few meters above la Fájara spring there is a cave known as la Fájara cave (*Figure 54*). La Fájara cave has been explored for 1500 m and it comprises a labyrinthine system of karst conduits. The cave functions as a trop plein (overflow) after heavy rainfall events. Thus, la Fájara spring (*Figure 55*) is a siphon of the lower parts of the network of karst conduits forming the phreatic part of the network.

13.4 Climate

The catchment area of la Fájara spring has a typical Mediterranean climate with hot summers and mild winters as well as a bimodal rainfall in winter and spring. The mean annual rainfall is 573 mm and the mean annual temperature is 18° C. Spectral analysis of time series of precipitation data (Pérez and Andreo, 2006) have shown that apart from the annual periodicity there are climatic cycles with periods of 2-2.8 years, 3.5-4.5 years, 7 years, 14.6 years and 25 years. These cycles seem to be related to the quasi-biennial oscillation, the North Atlantic Oscillation and solar activity.

13.5 Hydrogeology

Autogenic recharge

The recharge of the aquifer is autogenic, that is, it comes from the rainfall that falls over the aquifer catchment. There are no closed karst depressions (dolines) in the landscape but there are potholes. The recharge is mainly along fissures, fractures and bedding planes that have an E-W direction and define the E-W flow direction. Recharge is concentrated along large fractures and potholes. The catchment area of la Fájara is largely comprised of permeable Triassic marables, and the impermeable base of the aquifer is formed by Paleozoic schists. The mean annual infiltration has been estimated as 379 mm/year (IGME, 2001) which implies 66% of the rainfall. Thus the mean recharge is estimated to be around 6.5 hm^3/year.

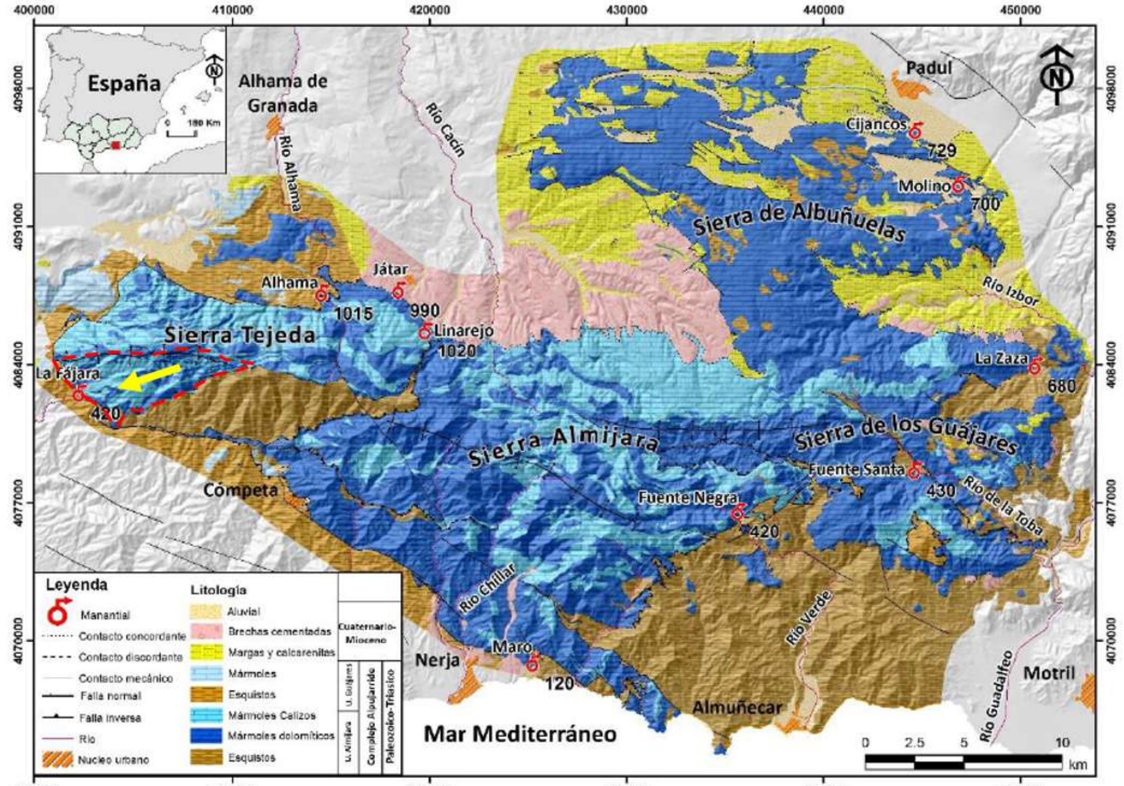


Figure 52: Hydrogeological map of the catchment area of the "la Fajara" spring. Figure taken from Prieto and Andreo (2017).

Groundwater flow system

The groundwater flow follows the stratification of the flank of the anticline and the E-W direction of the fold as seen in *Figure 53*. The mean discharge of la Fájara spring is 100 l/s.

Hydrochemistry

The behavior of electrical conductivity and temperature are similar with a rapid decrease in both parameters when the discharge increases because of heavy rainfall. In the year 2003 this was of the order of 100 µS and 2-3^{o} C respectively (Prieto and Andreo, 2017). This implies a very strong underground connection between la Fájara spring and the recharge area. The mean values of the main ions are (Prieto and Andreo, 2017): Ca^{2+}: 57 mg/l, Mg^{2+}: 14 mg/l, Na^{+}: 3 mg/l, K^{+}: 1 mg/l, Cl^{-}: 4 mg/l, SO_4^{2-}: 11 mg/l, NO^{3-}: 3 mg/l, F^{-}: 0.2 mg/l, pH: 7.7, T 15.1 ^{o}C, CE: 338 µS/cm.

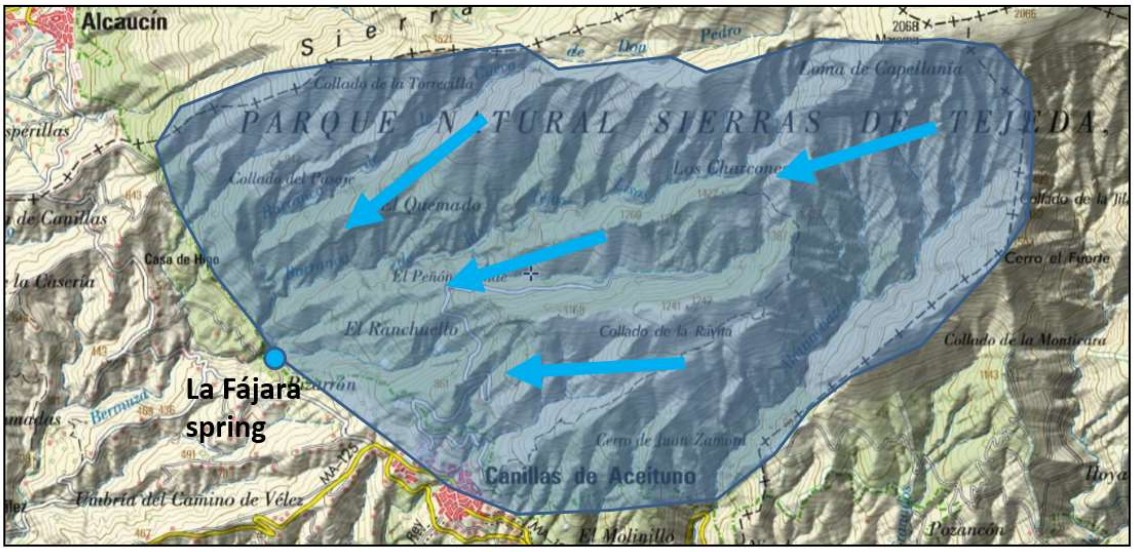


Figure 53: Directions of the flow of groundwater in the catchment area "La Fájara"

The hydrochemical facies are calcium bicarbonate type and calcium-magnesium bicarbonate type and they are of good quality for drinking. The hydrochemical facies are in accordance with the lithology of the catchment. The spring of la Fajara is certainly important for its water resources and for its ecological and environmental importance.

Figure 54: La Fájara cave which is an overflow of la Fájara spring. Photo from the Grupo de Exploraciones Subterráneas de la Sociedad Excursionista de Málaga.

Figure 55: La Fájara spring which is a syphon of the lower conduits connected with la Fájara cave (Figure 53). It has been explored by speleo-diving to -13 m. Photo from the Grupo de Exploraciones Subterráneas de la Sociedad Excursionista de Málaga.

13.6 Hydrodynamic characteristics of the springs

La Fájara spring is characterized by large oscillations of flow. The basic characteristics of the hydrological regime of la Fájara spring are:

- Average flow, $Q_{ave} = 0.183$ m^3/s
- Minimum flow, $Q_{min} = 0.01$ m^3/s
- Maximum flow, $Q_{max} = 20.7$ m^3/s

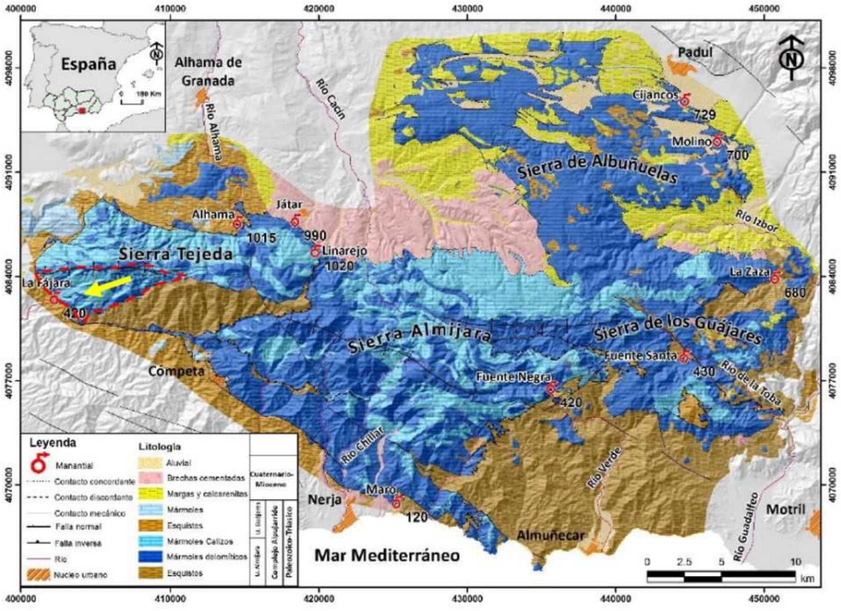
Spectral analysis on time series discharge data from la Fájara (Pérez and Andreo, 2006) have shown that apart from the annual periodicity there is an inter-annual periodicity of around 20 years that seems to be related to a 25 year cycle found in rainfall as described in the climatology section. Based on the discharge curve, the la Fájara recession coefficient has a value $\alpha = 0.021$.

13.7 Data available for the project

1. La Fájara spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 hour	5 year	From 19/05/2015 to 30/09/2017
Electrical conductivity	1 hour	1 year	From 12/04/2016 to 03/03/2017
Temperature	1 hour	1 year	From 12/04/2016 to 03/03/2017

13.8 Summary

Pilot name	**LA FÁJARA**

Country	Spain	EU-region	Mountain areas
Area (km^2)	37	Lithology	Carbonatic marbles
Short description: La Fájara is the origin of the Bermuza river and is of great interest as a spring with a catchment on carbonate marbles. The catchment area is estimated to be around 37 km^2. The spring has concentrated outflow from the conduit system with a trop plain (La Fájara cave) that "explodes" after heavy rainfall events. The coordinates of the spring in the ETRS89 reference system are X = 402290, Y = 4082358, Z = 470 m.			
Monitored objects	Spring		
Monitored data	Discharge, temperature, EC,		
Contact person	Eulogio Pardo (e.pardo@igme.es)		

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- https://doi.org/10.3989/egeol.43395.509.

14 THE NETHERLANDS: MERGELLAND

14.1 Overview

"Mergelland" ("Marl country") is a region in the south of the Dutch province of Limburg (*Figure 56*). The name refers to the presence at shallow depth of limestone, called "Mergel" (Marl) by the local population. The area is known for its hilly countryside (which sticks out compared to the rest of the Netherlands), the natural beauty, and several picturesque villages and hamlets ("Mergelland", 2020).

The region is roughly bounded by highways A2, A79 and A76 and the Dutch-German and the Dutch-Belgian border (*Figure 56*). The Margraten Plateau can be considered as the centre of "Mergelland". This plateau is bounded by the valley of the river Meuse to the West and by the valley of the river Geul in the North. It is dissected by the valley of the Gulp brook and various dry valleys. The entire region is part of the catchment of the Meuse river (Van den Hoven & Van den Hoven, n.d.).

Due to the presence of loess deposits, the soils in Mergelland are fertile and are widely used for arable and dairy farming and fruit growing. Particular flora and fauna are present, for example on the slopes and in the smaller brook valleys. This has resulted in the designation of various nature areas, including Natura 2000 sites ("Natuur en Landschap", n.d.).

The brooks are fed by several relatively small springs (*Figure 56*). In many of these springs and brooks nitrate concentrations are above 50 mg/l, due to leaching of agricultural fertilizer. This eutrophication has led to changes in vegetation. High nitrate concentrations are also found in groundwater in the area, thus having an impact on public and private water supplies (Hendrix & Meinardi, 2004).

The main aquifer in the area is the "kalksteenaquifer" (limestone aquifer). The saturated thickness of the limestone aquifer varies from 0 to 180 meters with an average of 66 meters. The thickness of the unsaturated zone of the aquifer varies from around 75 meters on the plateaus to 0 meters in the valleys of the rivers and brooks where the aquifer is fully saturated. Only the upper 40 m of the limestone aquifer are thought to be karstified to a certain degree (Vernes et al., 2009). Caves in the limestone are all manmade. To the north this aquifer is covered by a second stratified aquifer of quaternary and tertiary deposits. The hydrogeological situation at the location of the springs varies.

The discharge of the springs has only been measured or estimated occasionally. No continuous measurements are currently carried out at the sites of the springs.

St Brigida spring

The Sint-Brigida spring is the only site with some discontinuous time series data available. The discharge of this spring is characterized by a lack of a fast discharge component (Teuling, 2001). The Sint-Brigida spring is the main source of the Noor brook, which flows to the southwest into Belgium. The entire hydrological system of the Noor sub catchment behaves more or less homogeneously (Teuling, 2001).

The data analysis to identify methods of classifying the typology of karst aquifers (deliverable D5.3) will be done using the time series data of the St Brigida spring.

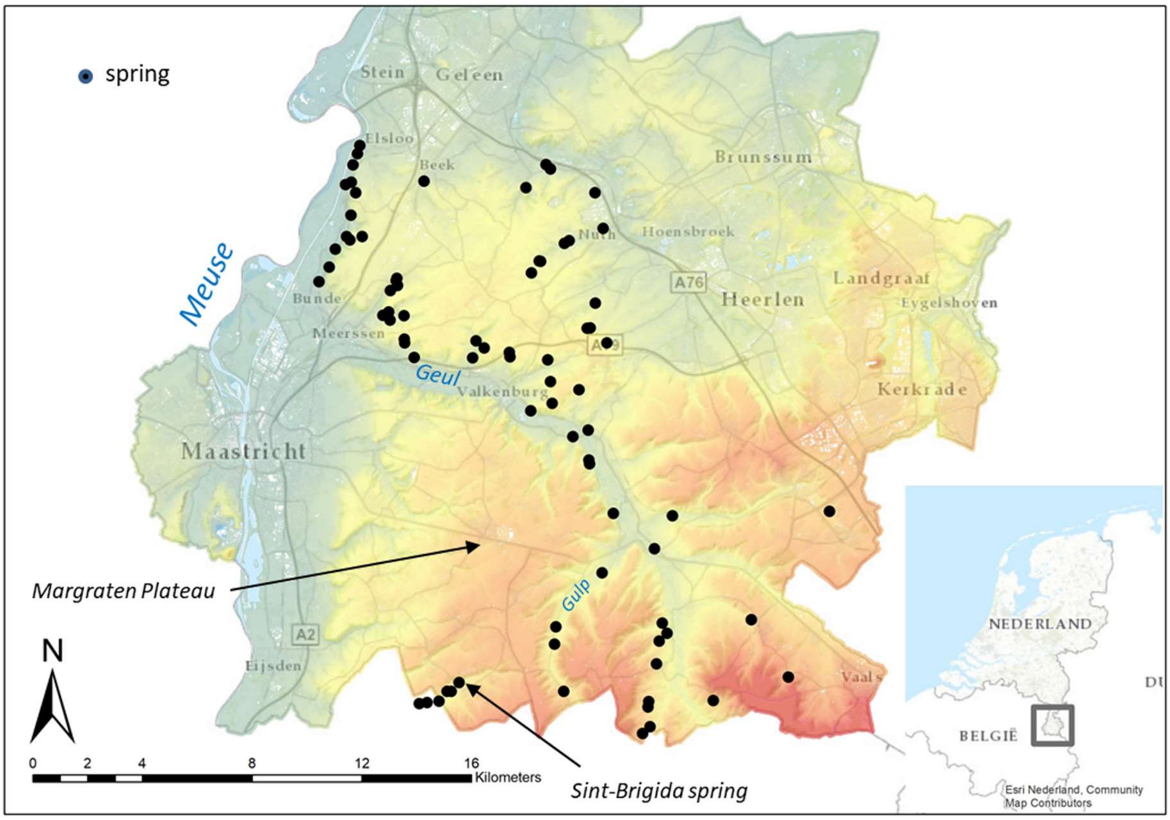


Figure 56: Location of "Mergelland" ("Marl country") and springs in the south of the Dutch province of Limburg. The Margraten Plateau can be considered as the centre of "Mergelland".

14.2 Geology

"Mergelland" is situated on the northern flank of the Rhenish Slate mountains (Rheinische Schiefergebirge), a chain of low mountains that stretches across Germany (the Eifel), Belgium and Luxembourg (the Ardennes) and the southernmost part of the Netherlands, and that predominately consist of Palaeozoic rocks ("Rijnlands leisteenplateau", 2020). To the north the area is bounded by the Roer Valley Graben, an active rift zone that stretches out across the southern part of the Netherlands, the north-eastern part of Belgium and North Rhine-Westphalia in Germany.

The Palaeozoic basement of the Rhenish Slate mountains dips in a north-westerly direction and is covered by marine Upper-Cretaceous rocks, and to the north by marine Paleogene and Neogene deposits. Fluvial and/or aeolian Quaternary deposits are present as a cover layer in nearly the entire area (Figure 57).

The lowermost part of the Upper-Cretaceous deposits consists of partly consolidated sands, silts and clays (Aken Formation, Vaals Formation). Silts and clays are dominant. The upper part is made up of soft limestone (Gulpen Formation, Maastricht Formation). The Gulpen Formation predominantly consists of soft, fine-grained limestone. The lower part contains 50-90% $CaCO_3$ and glauconite. The upper part contains 80-95% $CaCO_3$ and distinctive flint nodules which may constitute up to 20% of its volume. (TNO-GSN, 2020a). The Gulpen Formation matches the description of the Chalk in the United Kingdom (Van Rooijen, 1993). Within the Maastricht Formation two lithofacies can be distinguished (TNO-GSN, 2020b). In the southwestern part of Limburg, the Maastricht facies occur which are soft, fine to very coarse-grained yellow chalky limestones with intercalations of glauconitic limestones, hardgrounds and fossil beds. Flint is limited to the lower part. In the south-eastern part of Limburg, it consists of alternating hard and soft, light grey limestones (Kunrader facies). The overlying Houthem Formation, which is of Palaeocene age, also consists of soft limestone and together with the Gulpen and Maastricht formations makes up the *"kalksteenaquifer" (limestone aquifer)*. The thickness of these soft limestones varies from 0 to 185 meters with an average thickness of 75 meters.

Younger Paleogene and Neogene deposits consist of an alternation of fine to medium sands and clays (Landen Formation, Tongeren Formation, Rupel Formation, Breda Formation). These are covered by coarse sands and gravels (Beegden Formation) and loess (Boxtel Formation) on the plateaus and hillslopes; and by local fluvial deposits (Boxtel Formation) in the brook valleys.

According to Van Rooijen (1993) a mature karst system is not present in the "kalksteenaquifer" (limestone aquifer) in Mergelland. Caves are all man-made. Although major solution caves are not known to exist, at a tunnel construction site near Maastricht cavities of substantial size were encountered (personal communication Björn Vink, 2019). However typical karst features are present: sink holes or dolines, dry valleys, narrow, vertical solution pipes and at the top of the chalk a residual of flint-bearing clay and sandy loam.

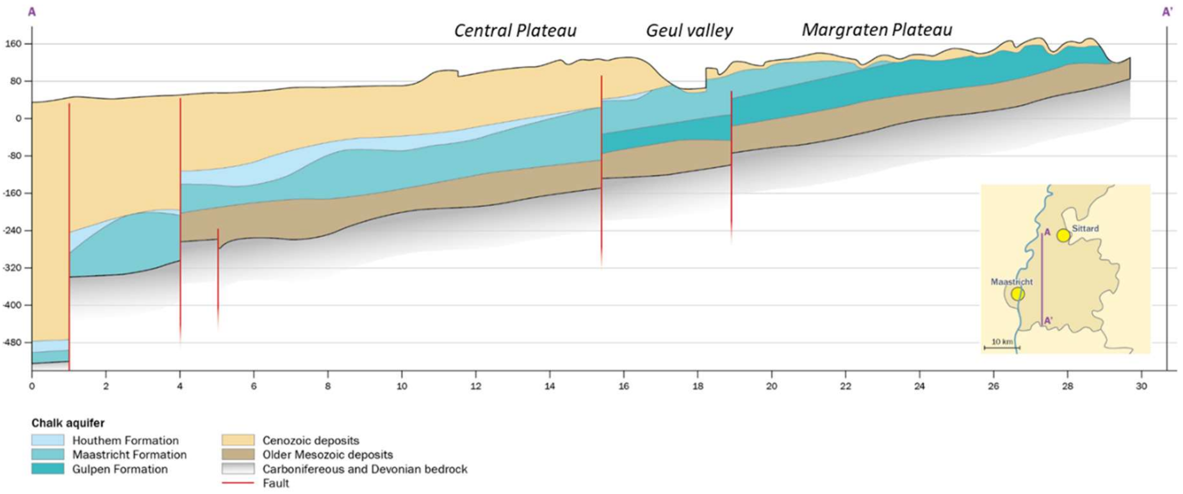


Figure 57: North-south geological cross-section trough South-Limburg and "Mergelland" (Vernes et al., 2018)

14.3 Geomorphology

The Margraten Plateau can be considered as the centre of "Mergelland". This plateau is bounded by the valley of the river Meuse to the west and by the valley of the river Geul in the north. The plateau is dissected by the valley of the Gulp brook and various smaller (dry) valleys.

The Sint-Brigida spring (Figure 58) is located just south of the Margraten Plateau, on the northern slope of the valley of the Noor brook. Dry valleys are present in the near vicinity.

Figure 58: Sint-Brigida spring, the source of the Noor brook.

14.4 Climate

According to the Köppen classification system, the climate of Mergelland is a temperate oceanic climate, code Cfb, with mild winters and cool summers (“Klimaat van Nederland”, 2020). The daily mean temperature at Maastricht is 10.7 °C, the annual precipitation is around 800 mm and the annual reference evaporation (Makkink) approximately 600 mm (KNMI, 2020).

14.5 Hydrogeology

The “kalksteenaquifer” (limestone aquifer), comprising the soft limestone of the Gulpen, Maastricht and Houthem formations, is the main aquifer in Mergelland (Figure 57). A subdivision can be made in the area in the north of the river Geul where the aquifer is overlain by Paleogene and Neogene deposits, of which the lower part acts as an aquitard; and the area in the south where these deposits are absent. The character of the “kalksteenaquifer” therefore changes from a confined aquifer in the north to a phreatic aquifer in the south.

The saturated thickness of the limestone aquifer varies from 0 to 180 meters with an average of 66 meters; the thickness of the unsaturated zone of the aquifer varies from around 75 meters on the plateaus to 0 meters in the valleys of the rivers and brooks where the aquifer is fully saturated.
Due to the low permeability of some of the Paleogene deposits a perched water table with a regional extent is present just north of the river Geul above the “kalksteenaquifer”. Several small streams that drain this area become losing streams once the edge of the aquitard is crossed and some streams disappear completely. Springs are present, both in the northern and southern part of the “kalksteenaquifer” (see *Figure 56*). In the northern part these springs generally occur on the slopes of the valleys, at the level of poorly permeable layers within the Paleogene and Neogene

deposits. These springs are not fed by the “kalksteenaquifer” and could therefore have a different behaviour. Also, in the southern area, where the “kalksteenaquifer” is phreatic, there are springs which are not fed by the “kalksteenaquifer”, but by small local permeable zones present in fractured sand- and siltstones within the underlying generally poorly permeable Vaals and Aken formations.

Some of the locations of the springs coincide with the interface between the “kalksteenaquifer” and the underlying Vaals and Aken formations, one of which is the location of the Sint-Brigida spring. Further research is needed to get a better understanding of the hydrogeological system of the various springs.

The “kalksteenaquifer” is exploited for public water supply, industry (for example breweries, mineral water production and soft drink industry) and for agricultural purposes.

At various locations groundwater levels in the “kalksteenaquifer” are measured on a regular basis. Based on these data, maps were created (Vernes et al., 2009) that clearly reflect the different character of the aquifer in the north, where it is confined, versus the south where it is phreatic.

14.6 Hydrodynamic characteristics of the springs (and river)

The discharge of the springs has only been measured or estimated occasionally, except for the Sint-Brigida spring for which a (discontinuous) time series over the period of 12 February 1994 to 23 October 2001 exist. Based on single measurements and estimates provided by Hendrix & Meinardi (2004) for the end of 2001, the discharge rate of the springs is small compared to springs in mature karst systems and varies between 0.01 and 12 l/s (northern area) and between 0.05 and 23.8 l/s (southern area). Time series of the discharge of the Sint-Brigida spring for the period of 22 June 1994 – 23 April 2000 show fluctuations in discharge from 0 (dry) to 55 l/s. Some of the larger springs are thought to be related to karst features (Hendrix, 1990).

Teuling (2001) concluded that the discharge of Sint-Brigida spring is characterized by a lack of a fast discharge component. The Sint-Brigida spring is the main source of the Noor brook. The entire hydrological system of the Noor sub catchment behaves more or less homogeneously (Teuling, 2001). The brook flows into Belgium where it enters a tributary of the Meuse river.

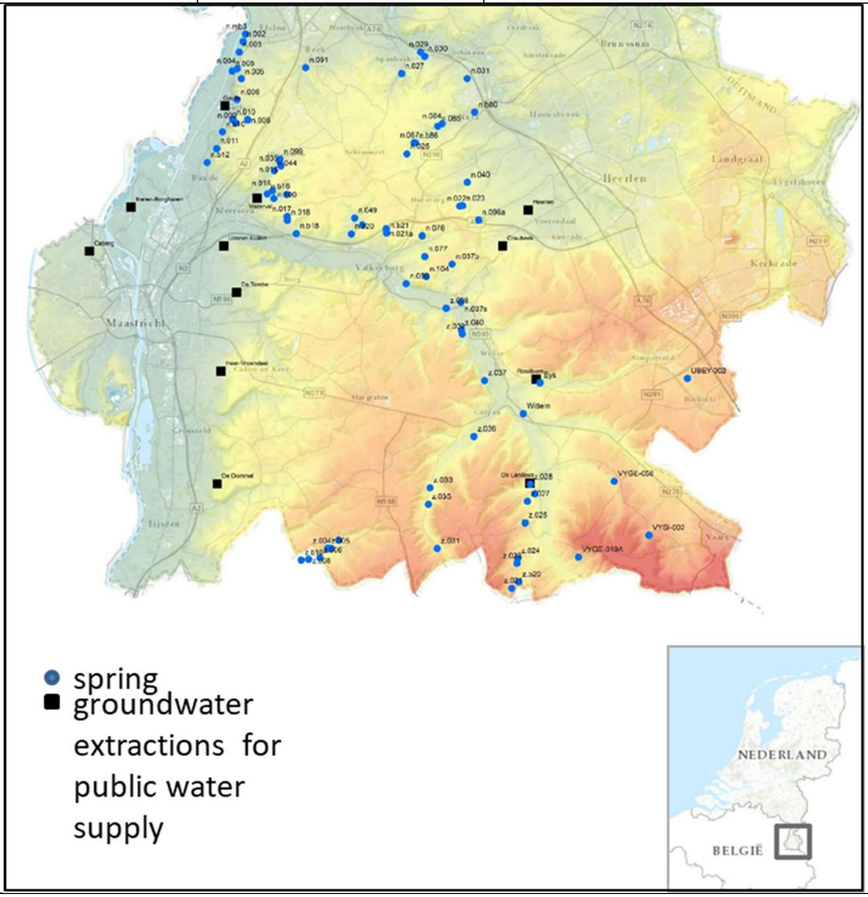
14.7 Data available for the project

1. Mergelland, springs			
Data type	Time step	Monitoring period	Time period
Level	-	-	-
Discharge: - St Brigida spring - Other springs	Every quarter-hour Occasionally	>10 year unknown	1994-2002 unknown
Temperature	One a year 4 times a year	>10 year	1991 – 2006 2007-present
Electrical conductivity	Once a year 4 times a year	>10 year	1991 – 2006 2007-present

1. Mergelland, springs			
Data type	Time step	Monitoring period	Time period
pH	Once a year 4 times a year	>10 year	1991 – 2006 2007-present
Dissolved oxygen O_2	One a year 4 times a year	>10 year	1991 – 2006 2007-present
Suspended matter	-	-	-
Major anions/cations	Once a year 4 times a year	>10 year	1991 – 2006 2007-present
Isotopes (tritium)	1 time per approx. 8 years	>10 year	2001 - 2018
Turbidity	-	-	-
Nutrients (NO3; PO4)	Once a year 4 times a year	>10 year	1991 – 2006 2007-present
TOC/DOC	Once a year 4 times a year	>10 year	1991 – 2006 2007-present
Other: metals, trace elements	Once a year 4 times a year	>10 year	1991 – 2006 2007-present

2. Mergelland, monitoring wells			
Data type	Time step	Monitoring period	Time period
Level	Once every 2 weeks / once a day	>10 year	different measurement periods
Discharge	-	-	-
Temperature	Once a year / Once every 2 years	>10 year	1992-2015
Electrical conductivity	Once a year / Once every 2 years	>10 year	1992-2015
pH	Once a year / Once every 2 years	>10 year	1992-2015
Dissolved oxygen O_2	Once a year / Once every 2 years	>10 year	1992-2015
Suspended matter	-	-	-
Major anions/cations	Once a year / Once every 2 years	>10 year	1992-2015
Isotopes	-	-	-
Turbidity	-	-	-
Nutrients (NO3; PO4)	Once a year / Once every 2 years	>10 year	1992-2015
TOC/DOC	Once a year / Once every 2 years	>10 year	1992-2015
Other: metals, trace elements	Once a year / Once every 2 years	>10 year	1992-2015

14.8 Summary

Pilot name	**Mergelland**		
Country	The Netherlands	EU-region	North-western Europe
Area (km^2)	617	Lithology	Chalk
Short description: Mergelland is the southernmost part of the Netherlands. The area consists of a number of plateaus, dissected by small valleys. The main river is the river Geul. Small springs are present at various locations. In the southern part these springs are fed by creataceous aquifers, to the north by Cenozoic aquifers. The Sint-Brigida spring, located on the southern edge of the area, is the only spring with a time series of discharge measurements.			
Monitored objects	Springs, wells and precipitation.		
Monitored data	Groundwater levels, discharge (occasionaly), temperature, electric conductivity, major anions/cations, stabile isotopes, nutrients (NO3;PO4), TOC/DOC, other.		
Contact person	Mariëlle van Vliet (marielle.vanvliet@tno.nl) & Ronald Vernes (ronald.vernes@tno.nl)		

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15 ROMANIA: MONEASA AREA

15.1 Overview

In-depth studies of the karst hydrogeology in the Codru Moma mountains were carried out by I. Oraseanu. Since these studies best illustrate the study area, we will give extensive quotes from them.

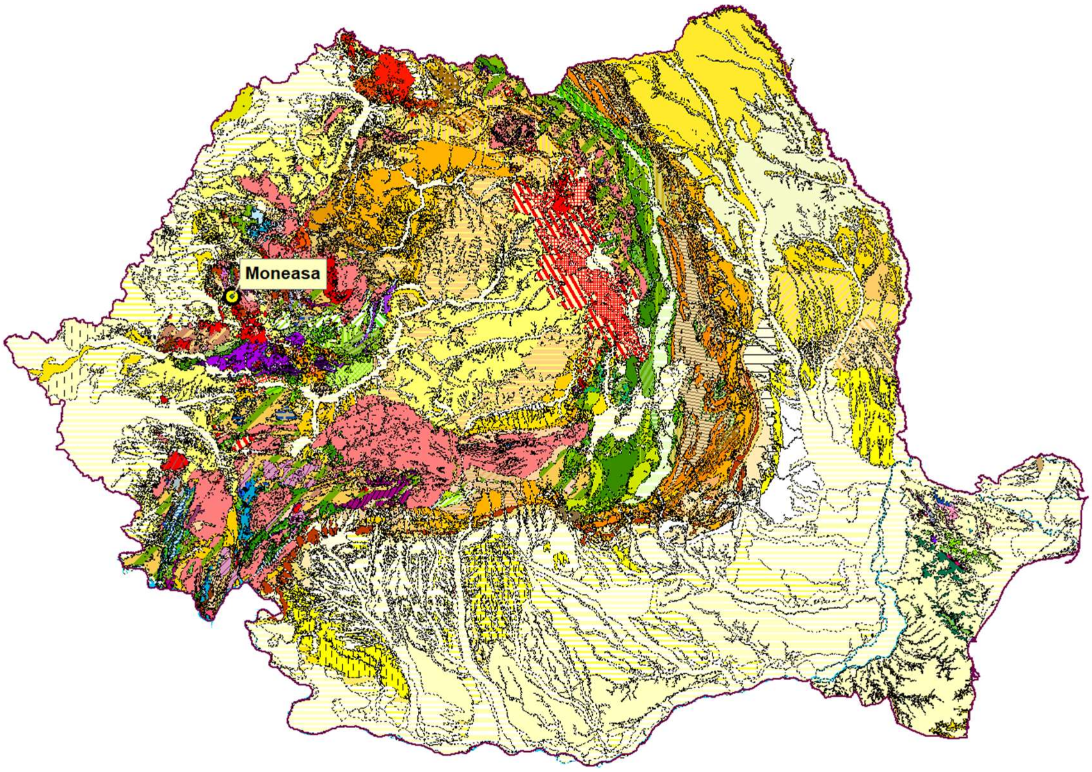


Figure 59: Location of the test - site

The test site is in the Moneasa resort region, situated in the Apuseni Mountains in the western-central part of the Codru-Moma massif, and has morphological variety due to a complex geological structure. Moneasa resort is well known for its thermal waters (24 to 32.8°C), which are exploited through four springs and three wells. Despite the low altitude, Moneasa resort is located in a submontane landscape, with the narrow valley of the Moneasa river surrounded by higher ground reaching over 700 m in elevation. The slope gradients exceed 15 degrees over much of the area (51.5% of the total surface area). Near the resort, these are covered by hardwood forests where Fagus silvatica is the predominant species (forests represent 85% of the township territory). The natural therapeutic factors include the moderate temperate continental climate, the sedative-indifferent bioclimate with stimulating-tonic trends, and the mesothermal oligomineral waters.[2]

The Codru-Moma Mountains extend over an area of about 1200 km^2, located in the western part of the Apuseni Mountains, and take the form of a NW-SE striking nappe system, bounded laterally by two Neogene basins: that of Crișu Negru (Beiuș) to the NE, and that of Crișu Alb (Zarand) to the SW. They consist of two zones which are quite distinct in terms of topography: the Codru Mountains to the north, and the Moma Mountains to the south. These are separated by the Moneasa valley and by its tributary Boroaia in the western half, and by the Lugii valley and the

Briheni brook further to the east. Carbonate terrains of the Codru-Moma Mountains occupy an area of 169 km^2, distributed as follows:

- Dumbrăvița de Codru-Moneasa-Dezna area (66 km^2);
- Clăptescu area (13 km^2);
- Vașcău plateau (90 km^2).

The study area is the Dumbrăvița de Codru-Moneasa-Dezna karst system, the area focusing on the Grota Urșilor - Băilor Brook and the Moneasa Brook.

15.2 Geology

The Codru domain, with formations incorporated in the Codru nappes, include a crystalline basement. This is overlain by sedimentary deposits consisting of thick Permian-Werfenian molasse deposits, overlain by predominantly carbonate facies deposited up to the Early Jurassic period. A subsequent sea retreat episode lasted during the Middle Jurassic, before the Codru domain was again covered by sea during the Tithonic-Neocomian time interval.

Between the Crișu Negru stream to the north and the Moneasa spa to the south, carbonate deposits form a continuous strip, incorporated in the generally homoclinal, eastward dipping geological structure of the central part of the Codru Mountains. This main strip, consists of Triassic limestones and dolomites with average outcrop widths of 2-3 km. To the east there is a second, discontinuous, limestone strip with average outcrop widths of only 50-100 m, which consists of Early Jurassic limestone.[2] The two carbonate strips are separated from one another by thick deposits consisting mainly of Norian and Rhetian shales and sandstones, which are virtually impermeable and thus isolate the groundwater located in each of the two carbonate strips. The main carbonate strip is underlain by Werfenian quartz sandstones, while the secondary limestone strip is overlain by flysch type deposits of Tithonic-Neocomian age. The lower half of the eastern slope of the ridge and the streambed of Ursului brook are covered by quartz sandstone scree and boulders deposits, which frequently cover the Early Triassic deposits. In the Codru-Moma Mountains, outcrops consist of sedimentary deposits which belong to the Finiș, Moma, Vașcău and Colești nappes.

From a geological point of view, the Moneasa area is situated in the area where the Moma Nappe thrust is over the Finiș Nappe. The Finiș Nappe formations make up a homocline that faces approximately North-South, and contains the Permian Rhyolitic Formation and the Werfenian quartzitic sandstones. They comprise thick predominantly limy facies including black dolomites (Anisian), black limestones with cherts - the Roșia Formation (Ladinian), white dolomites and violet breccious limestones (Carnian), marly, argillaceous shales and silty marls interbedded with rare decimetric black limestones and quartzitic sandstones - Codru Formation (Norian), argillaceous or silty shales with rare decimetric interbeds of dolomites, limestones and quartzitic sandstones - the Carpathian Keuper (Rhaetian), massive nodular and breccious red limestones - "Moneasa marble" (Lower Jurassic) followed by a flysch-like formation consisting of interbeds of marls, shales and sandstones (Tithonic and Neocomian).[2]

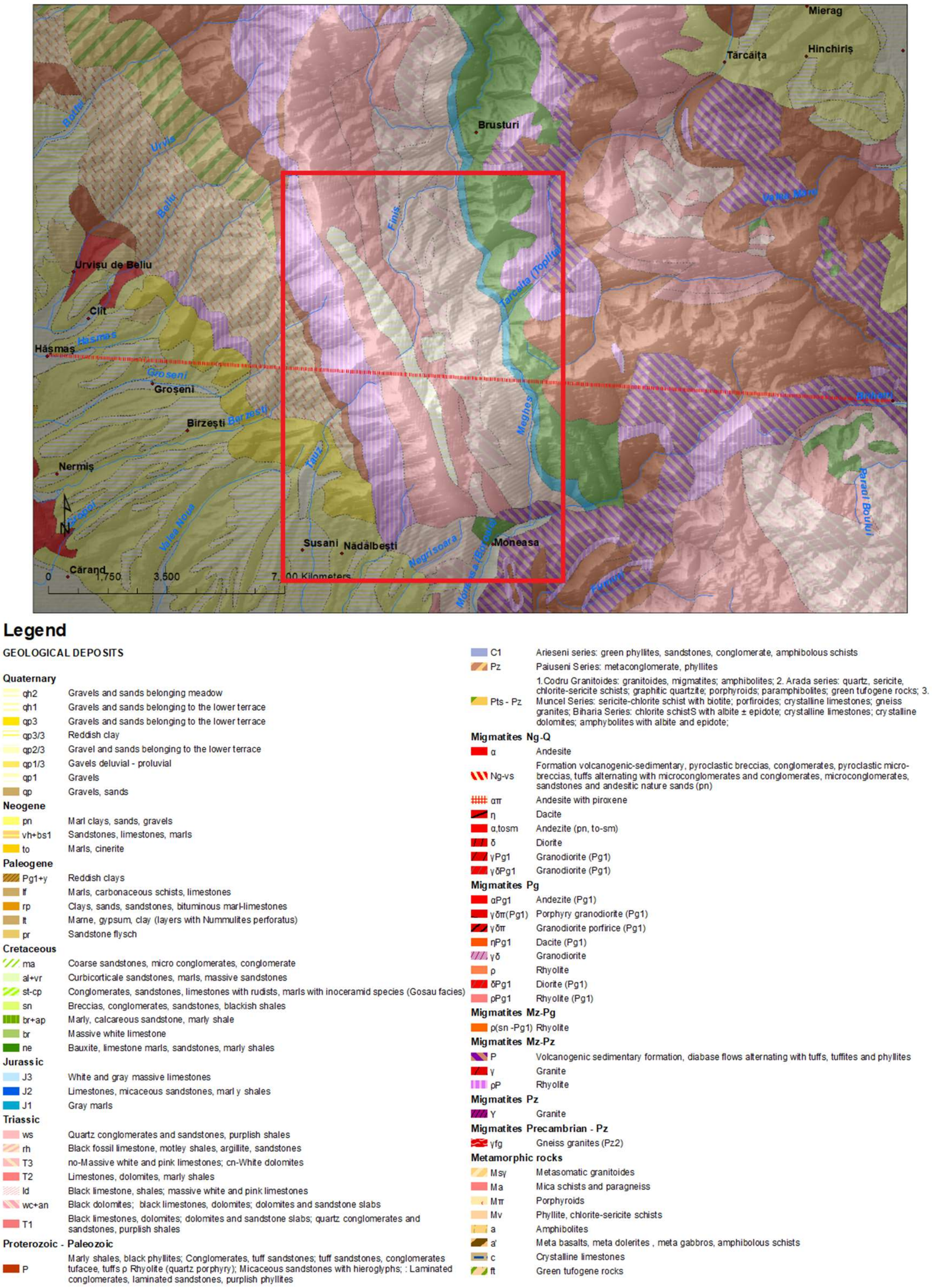


Figure 60: Geological Map; Source: Geological Map of Romania, scale 1:200.000, author Geological Institute of Romania.

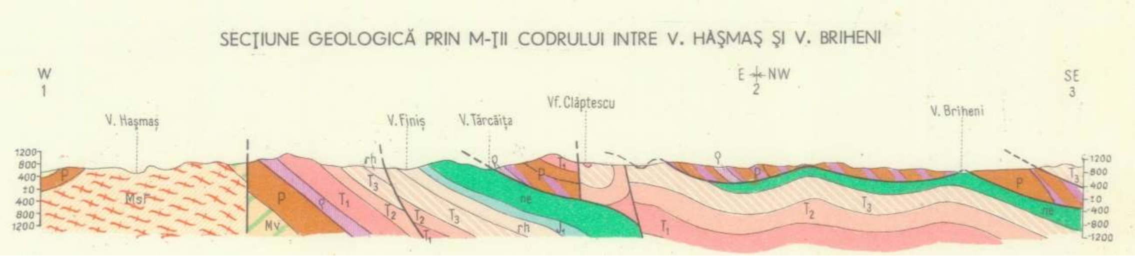


Figure 61: Cross section of Codru Moma Mountains; Source: Geological Map of Romania, scale 1:200.000, Brad, author Geological Institute of Romania.

15.3 Geomorphology

The topography of the Codru Mountains closely mirrors their geological structure and make-up. This includes three main mountain ridges, which strike roughly north-south and incorporate hard rocks of Permian age. Those ridges bound two depressions, which are formed of less competent rock formations and are occupied by the upper reaches of the longest rivers in those mountains, Finiș and Tărcăița. Water in the southern part of the Codru Mountains is collected by the Moneasa brook, a tributary of the Dezna stream, which is in turn a tributary of Crișu Alb river. The valley of Moneasa brook is tectonically controlled, closely following the strike of the overthrust plane of the Moma Nappe over the Finiș Nappe. In the karst area the stream tributaries, that are excavated mainly in carbonate formations (Scărița, Megheș, Băilor, Pietros), only come only from the right side. Băilor brook is mainly supplied by water discharged through Grota Ursului outlet cave. The underground cavities in the Moneasa area consist of several caves and potholes, including: Peștera cu Apă de la Moară cave (2012 m), Grota Ursului cave (250 m), and the pothole in Teia valley (1337.5 m long, and -90 m deep).[2]

15.4 Climate

The climate of the Moneasa area is continental, with moderate mountains, and some Mediterranean influence. The mean annual air temperature is 7.9°C. There is a moderate air humidity, with a mean value of 77% which varies by ~10% between the cold and warm season. The annual average cloud cover is 6 tenths and the effective sunshine duration is 2035 h/year. The average annual precipitation is 788 mm, with a hydrological deficit in May and July-September. In Moneasa the exposure to the west and the nature of the valleys where the resort is located result in a milder deficit. The snow layer can develop from October until April, with the greatest thickness in February (16.4 cm), and 98 mm water is contributed from melted snow during the whole year. The average wind speed in the area is 4 m/s, with winds predominantly from the ESE. General climate data for the study area were obtained from the CARPATCLIM database, with a spatial resolution of 0.1 × 0.1º grid (WGS 1984 reference system). These are spatially interpolated data from a regional weather station network for the 1961–2010 time interval.

15.5 Hydrogeology

The study area is the Grota Ursului karst system. The description is found in Orăseanu (2010): "Considered in global terms, the karst area which extends between Brătcoaia, Tinoasa, Izoi and Moneasa, together with its catchment area that extends further to the west up to Izoi ridge, makes up a single karst system, part of which displays a thermal character in its southernmost end, and whose underground water flow is directed from north to the south, discharging mainly through Grota Ursului spring and the thermal outlets” (*Figure 62*).

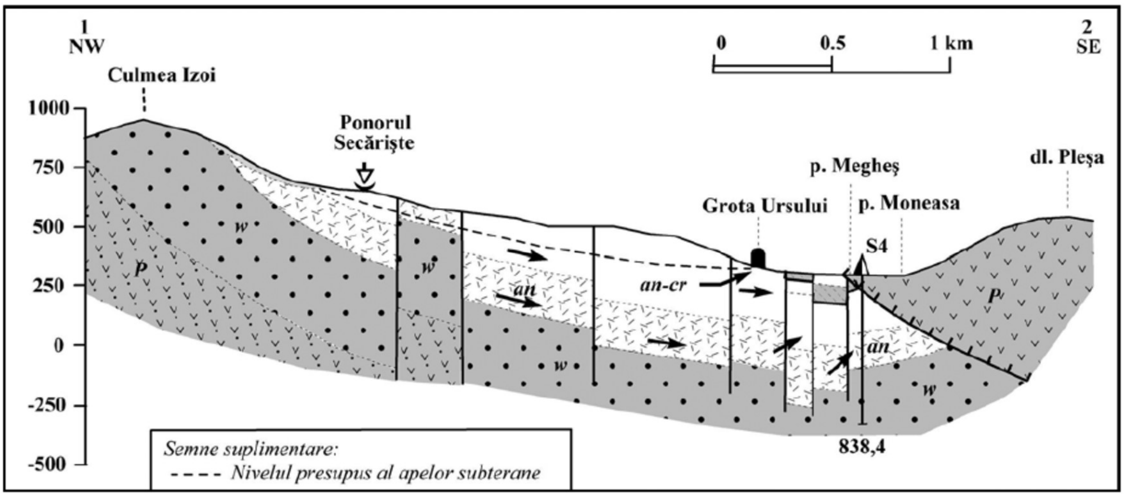


Figure 62: Cross section between Irzoi peak and the confluence between Megheș and Moneasa brooks. Source:Orașeanu I., 2010.

The thermal waters from Moneasa, both those from the natural springs as well as those encountered through drilling, are karstic in nature, arising from the carbonate deposits of the Finiş homocline, near the contact with the impermeable deposits of the Moma Thrust. The springs on p. Băilor emmanate from the carbonate deposits, on a 180 m long alignment, located upstream of where the brook reaches the Permian deposits. From a geothermal point of view, the whole area of the Băilor brook is an anomalous area with the maximum near spring 4, (A. Apostol et. al., 1975). The water which cannot be carried within this system, as a consequence of the limited transfer capacity of the karst channels and fractures, flows toward the east, through overflow springs in the Megheș brook catchment area (*Figure 63*). Connections between the water sinking into the swallets in the Brătcoaia and Izoi-Tinoasa karst depressions, and the cold and thermal outlets situated along Băilor and Megheș brooks, have been delineated by tracer tests. Băilor brook orginates from Grota Ursului cave and it receives a further significant inflow of thermal water, downstream from this outlet.

The chemistry of the cold and thermal karst waters in the Moneasa-Tinoasa area is calcium-magnesium bicarbonate with low mineralization (200-400 mg / l). Cold waters are more mineralized than warm waters. At the springs on the Băilor brook, there is an increase in the water temperature and a decrease in its mineralization as it approaches the overhang plan of the Moma Thrust. Over time, the chemical composition of the spring water undergoes large fluctuations, the most important variations being recorded in the ionic species Na +, K +, Cl- and SO4 -. These variations are natural and emphasize the presence of cold karst waters at the origin of the thermal waters from Moneasa.[6]

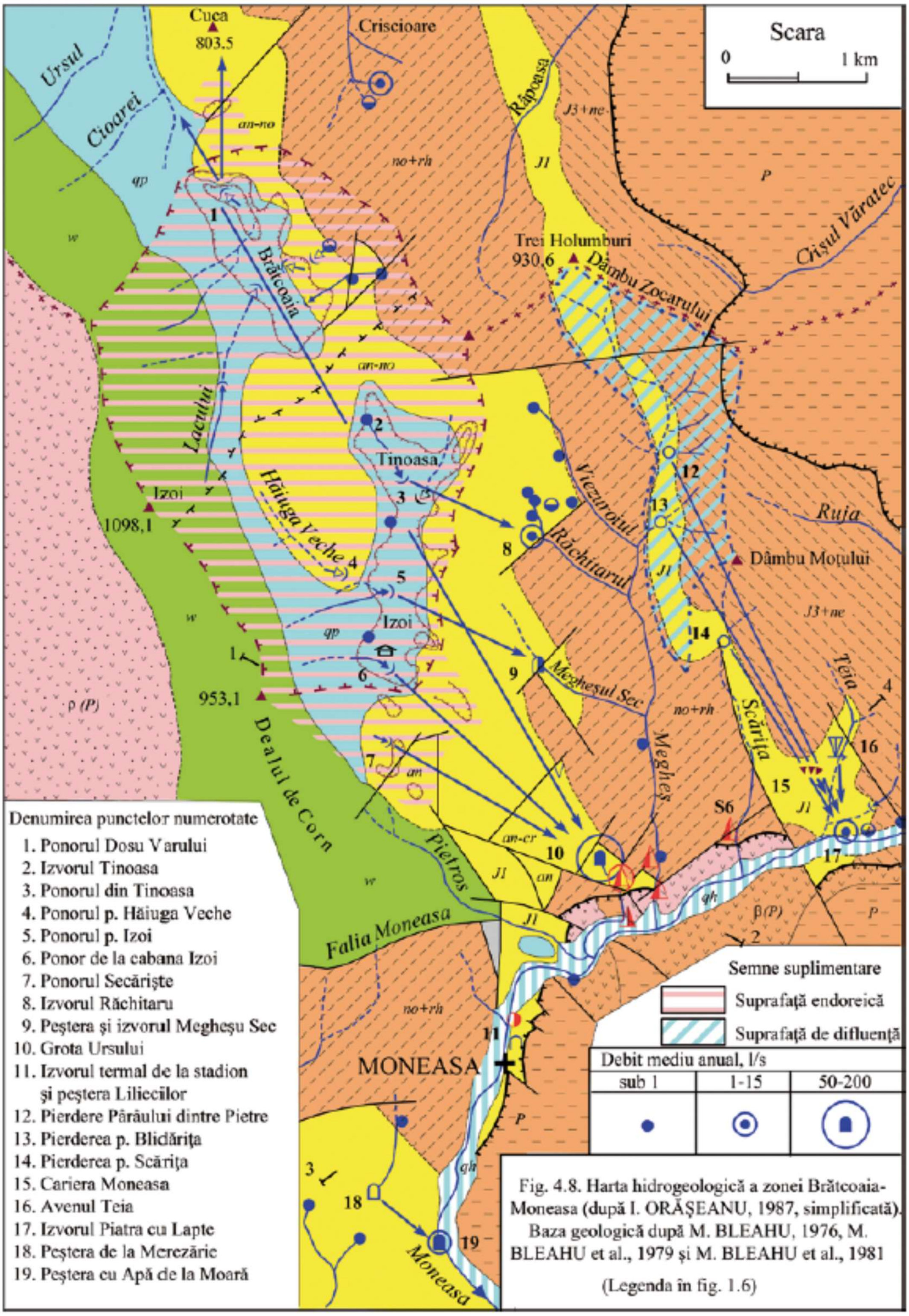


Figure 63: Hydrogeological Map of Bratcoaia - Moneasa area; Source: Orășeanu I., 2010.

15.6 Hydrodynamic characteristics of the springs (and river)

The flow rate is monitored in a systematic way in the gauging station (g. s.) installed by the National Institute for Hydrology and Water Management (NIHWM) on Băilor brook, in the area where the brook reaches the alluvial plain of Moneasa brook (Ciuperca g. s.). The gauging station has been in operation since 1976. The average flow rate for the time interval 1976-1997 is 198 l/s, with a range of 50 to 5,520 l/s. In order to measure the flow rate of the underground stream in Grota Ursului, a gauging station was installed inside the cave in the place where a mine passage intersects the underground stream. Monitoring was conducted from October 1997 to September 1998, and the average recorded flow rate was 58 l/s, while the average water temperature was 8.8°C.

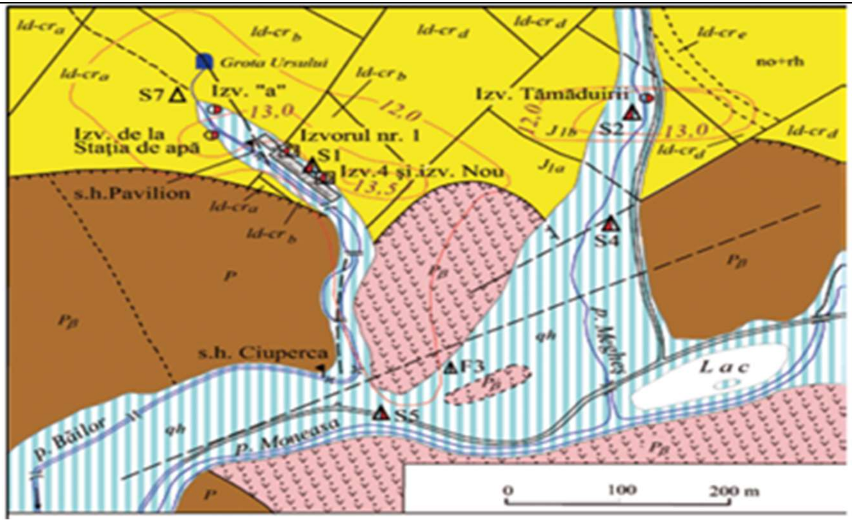
15.7 Data available for the project

1. Grota Ursului spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	2.3 year	10/1986 – 12/1987, 10/1997 - 09/1998
Major anions/cations	2 times a year	1.3 year	10/1986 – 12/1987
pH	2 times a year	1.3 year	10/1986 – 12/1987
Electrical conductivity	1 day	1 year	10/1997- 09/1998
Temperature	1 day	1 year	10/1997- 09/1998

2. Bălor spring			
Data type	Time step	Monitoring period	Time period
Discharge	1 day	1 year	10/1997- 09/1998
Electrical conductivity	1 day	1 year	10/1997- 09/1998
Temperature	1 day	1 year	10/1997- 09/1998

15.8 Summary

Pilot name	**Moneasa area**		
Country	Romania	EU-region	South East Europe
Area (km^2)	66	Lithology	Limestone

At the global scale, the karst area which extends between Brătcoaia, Tinoasa, Izoi and Moneasa, together with its catchment area makes up a single karst system, part of which displays a thermal character in its southernmost end, and whose ground water flow is directed from the north to the south, discharging mainly through Grota Ursului spring and the thermal outlets.	 Legend: qh – Quaternary – recent alluvia P – Permian: Sandstones, clay shales, diabases Jlb – Jurassic, Liasic: Red breccia limestone Jla - Jurassic, Liasic: Black limestones and black schists rh+no – Norian+Rhetian: Black limestone, yellow limestone, red and green schists ld+cr – Ladinian+Carnian: a: White limestone b: Limestone sandstones, yellow schists, black limestones c: Yellowish pink brecciated limestone d: Gray white dolomites e: Black limestone with chert
Monitored objects	Brooks (two), river gauge station (two), wells (two)
Monitored data	Discharge, temperature, EC, chemistry, (isotopes, fluorescence – occasionally)
Contact person	Diana Perșa (persa.diana@yahoo.ro)

15.9 References

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16 SYNTHESIS

The main characteristics of the study areas are summarized in the following table (*Figure 64*). There are 14 pilot sites for 13 EurogeoSurveys: one for each country except GB where two sites have been selected. Out of 14 sites, 11 are springs draining mostly limestone karst systems and one corresponds to springs located in a chalk aquifer. Two sites correspond to boreholes located in chalk aquifers. A special attention should be paid to those case studies where classical time series analysis methods have already developed and tested on springs.

Id	**Study area**	**Country**	**Region**	**Outlet alt.**	**Rock**	**Q_{mean}**	**Q_{max}**	**Basin area**	**P_{mean}**	**Karst type**
			*	[masl]	**	[m^3/s]	[m^3/s]	[km^2]	[mm/yr]	***
1	Gacka river springs	HR	Mount	460	L + D	15	70	515	1250	Auto
2	Nîmes spring	FR	Med	51	L	0.55	30	55	740	Auto
3	Vrelo Bune	BA	Mount	64	L	23.7	123 or 380 ?	1100	1756	Auto
4	Býčí Skála Spring	CZ	CE Eur	310	L	0.16	7.8	70	550	Auto+ Allo
5	Killeglan	IE	NW Eur	50	L	0.52	2.32	42	1040	Auto
6	St. Quinti & Cardener springs	Cat	Mount	≈ 944-1098	L	0.41	1,47	44.03	1055	Auto
7	Bedhampton & Havant springs	GB	NW Eur	TBC approx. 70-120	C	1.1	2.0	?	950	Auto+ Allo
8	Essendon Boreholes	GB	NW Eur	50	C	0.05	0.16	Bore hole	500	Auto+ Allo
9	Classical Karst aquifer	SI/IT	Med	5	L	35	140	750	1400 or 1570 ?	Auto
10	Waldbach spring	AT	Mount	920	L	3.50	31.60	800	2500	Auto
11	Nagy-Tohonya spring	HU	CE Eur	218	L	0.1	1.5	12.5	560 or 620 ?	Auto
12	Fájara spring	ES	Med	430 or 470 ?	M	0.183	20.7	37	578	Auto
13	Mergelland	NL	NW Eur	38	C	0.002	N/A (St Brigida spring 0.06 m3/s)	617	800	Auto+ Allo
14	Moneasa	RO	CE Eur	320	L	0.15	0.9	66	939	Auto+ Allo

*Figure 64: summary table of the main characteristics of the study areas (*Climate Region: Mount = mountainous, CE Eur= Central-Eastern Europe, NW Eur = North-Western Europe, Med = Mediterranean area; **Rock type: L = Limestone, D = Dolomite, C = Chalk, M = Marbles; ***Karst type: Auto=Autogenic, Allo=Allogenic)*

The location of the study areas is shown on the European map of the carbonate aquifers here below (*Figure 65*).

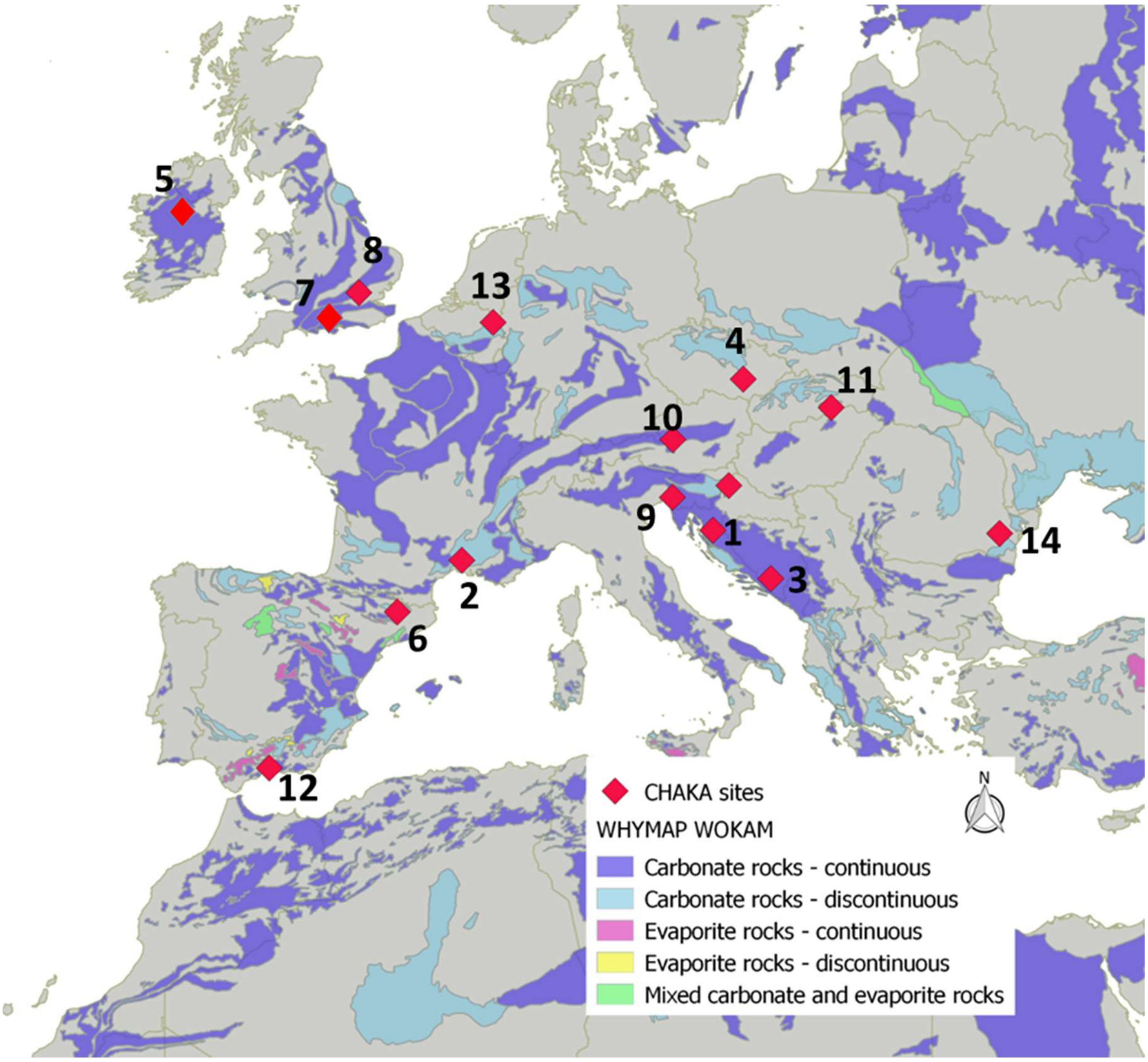


Figure 65: European map of carbonate rock aquifers with the location of the CHAKA sites

Considering the climate charcateristics of the case studies, there is a wide range of annual precipitation (500 to 2500 mm/yr, *Figure 66*) and evapotranspiration rates. Geomorphologically, most of the springs are located below 500 masl (*Figure 66*). Nevertheless, each spring drains a catchment located upstream, and therefore at higher elevations. The Austrian and Catalonyan springs are located in the Alps and Pyrenean Mountains.

The Mediterranean area is well represented with springs from the South of France, Spain, Slovenia, Croatia and Bosnia Herzogovina. Case studies located in the chalk (England and Netherlands) and limestones (Ireland) of North Western Europe are included.

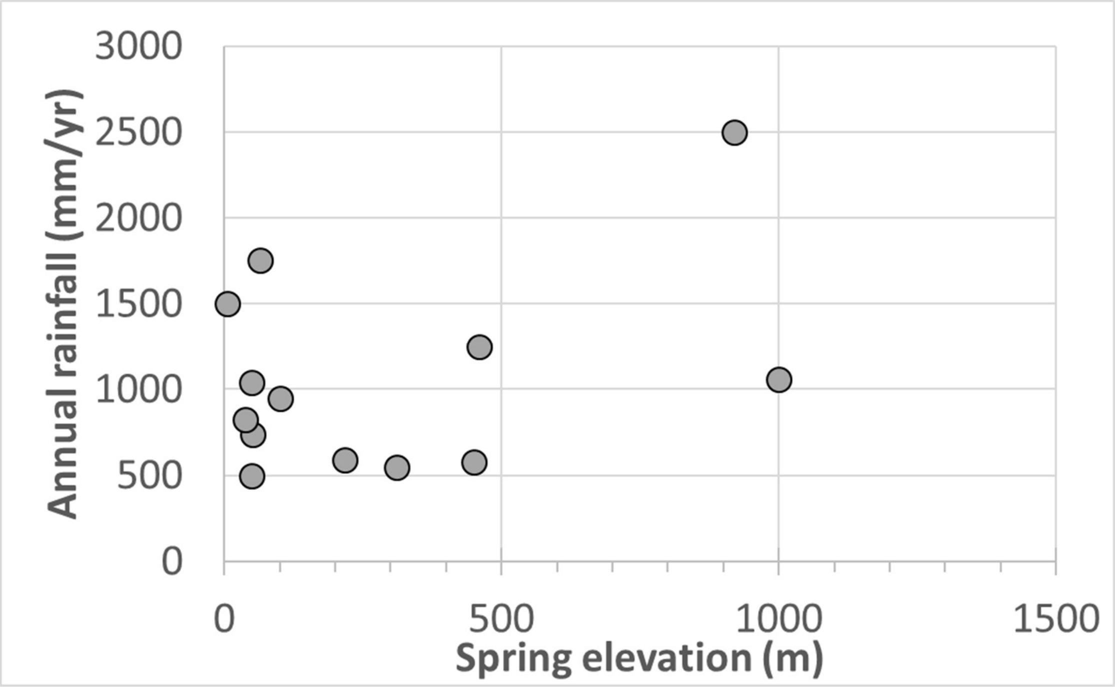


Figure 66: CHAKA study areas - diagram describing the mean rainfall on the catchement area as a function of the altitude of the monitoring point (mostly springs)

There is a classic positive relationship between the discharge rate at springs and the catchment surface area (*Figure 67*). Most of the catchment surface areas are less than 100 km^2 in extent. Their average discharge rate is less than 1 m^3/s (*Figure 67*). Three springs drain very large catchment with very high discharge rates of greater than 10 m3/s: Vrelo Bruna in Bosnia-Herzegovinia, Classical karst aquifer (Timivo spring) in Slovenia/Italy and Gacka river springs in Croatia. Overall, discharge rates vary widely from 0.1 m^3/s to 35 m^3/s.

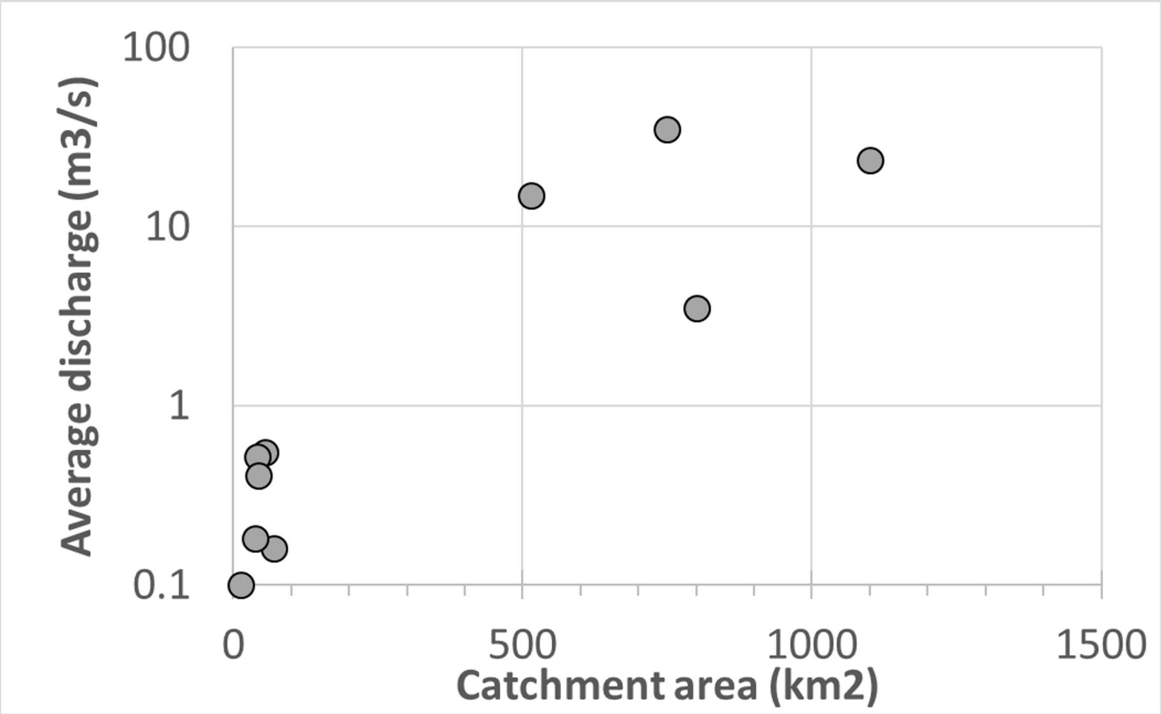
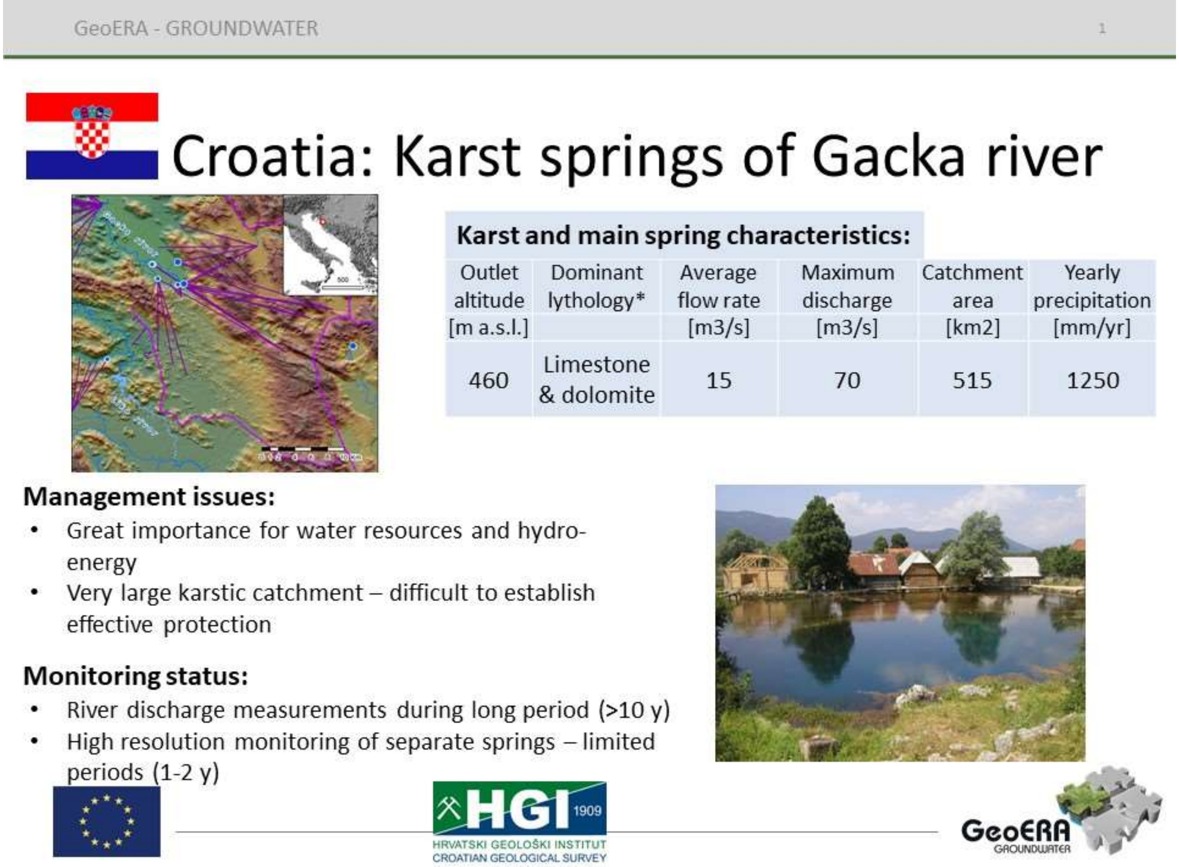


Figure 67: CHAKA study areas - diagram describing the average discharge rate at the monitoring point as a function of the catchment area

17 OUTLOOK

The time series data available for these case studies will be treated using analysis methods described in Deliverable 5.1. The results will be evalauated to identify the most appropriate and simple methods which are useful for characterizing the vulnerability of karst aquifers. These results will be described in Deliverable 5.3 of the project.

18 APPENDIX 1: SHORT PRESENTATIONS OF CASE STUDIES



Croatia: Karst springs of Gacka river

Karst and main spring characteristics:

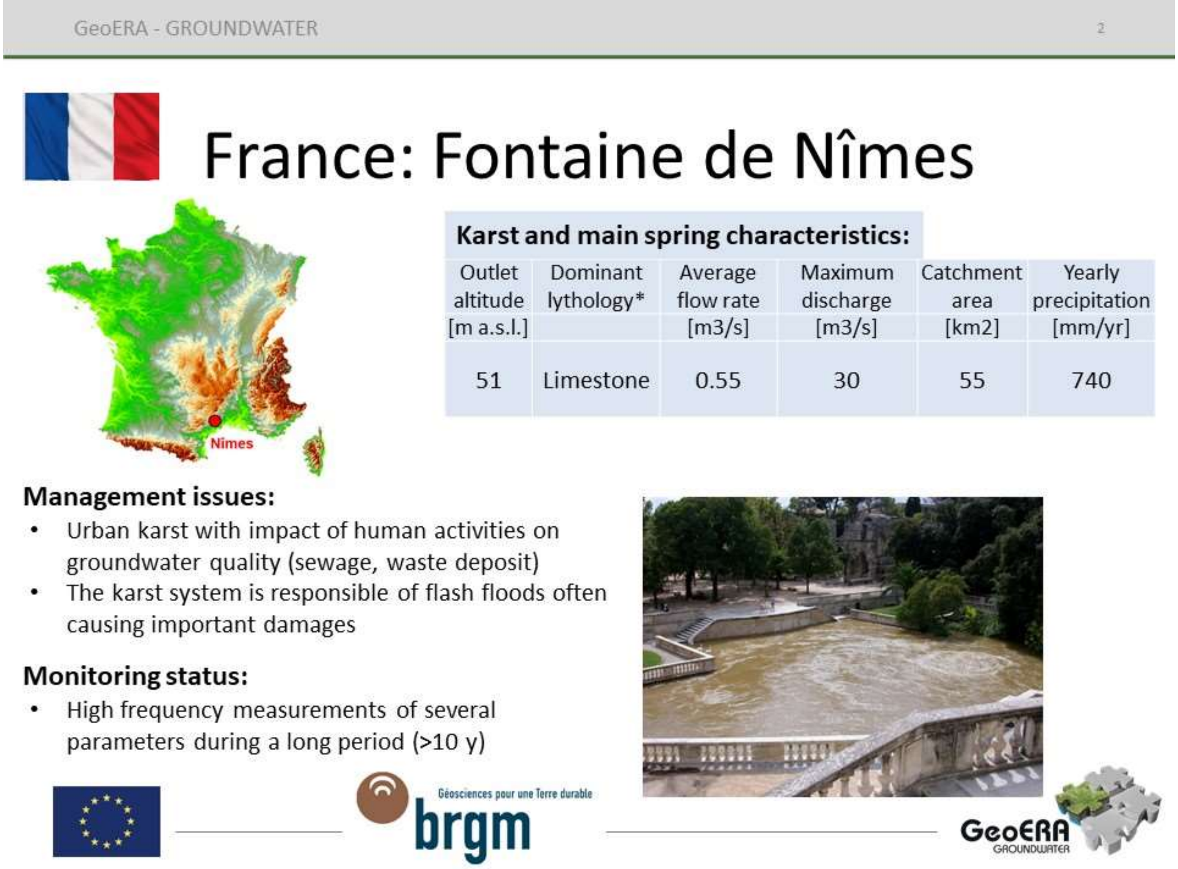
Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
460	Limestone & dolomite	15	70	515	1250

Management issues:

- Great importance for water resources and hydro-energy
- Very large karstic catchment – difficult to establish effective protection

Monitoring status:

- River discharge measurements during long period (>10 y)
- High resolution monitoring of separate springs – limited periods (1-2 y)



France: Fontaine de Nîmes

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
51	Limestone	0.55	30	55	740

Management issues:

- Urban karst with impact of human activities on groundwater quality (sewage, waste deposit)
- The karst system is responsible of flash floods often causing important damages

Monitoring status:

- High frequency measurements of several parameters during a long period (>10 y)

Bosnia and Herzegovina: „Vrelo Bune“

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
36	Limestone	23.70	380	750	1400

Management issues:

- Urban karst with impact of human activities on groundwater quantity and quality (sewage, waste deposit, hydropower plant)

Monitoring status:

- High frequency measurements of several parameters during a long period (>10 y)

Czech Republic: Býčí skála (Bull Rock)

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
310	Limestone	0,1	1,7	65	550

Management issues:

- Classic karst in Moravian Karst Protected Landscape Area
- Difficult for water balance
- Important for water supply

Monitoring status:

- Czech National groundwater monitoring
- Monitoring of water supply company
- Research monitoring

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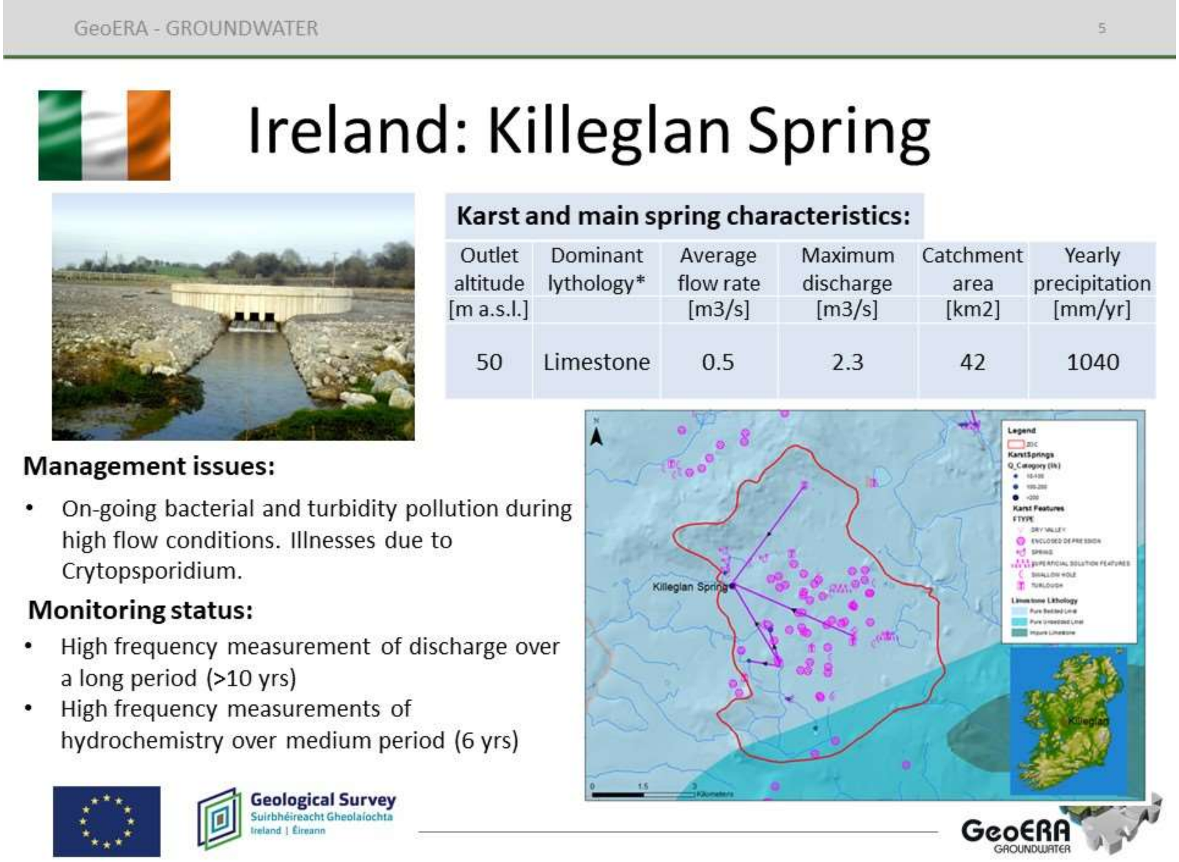

Ireland: Killeglan Spring

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
50	Limestone	0.5	2.3	42	1040

Management issues:

- On-going bacterial and turbidity pollution during high flow conditions. Illnesses due to Crytopsporidium.

Monitoring status:

- High frequency measurement of discharge over a long period (>10 yrs)
- High frequency measurements of hydrochemistry over medium period (6 yrs)

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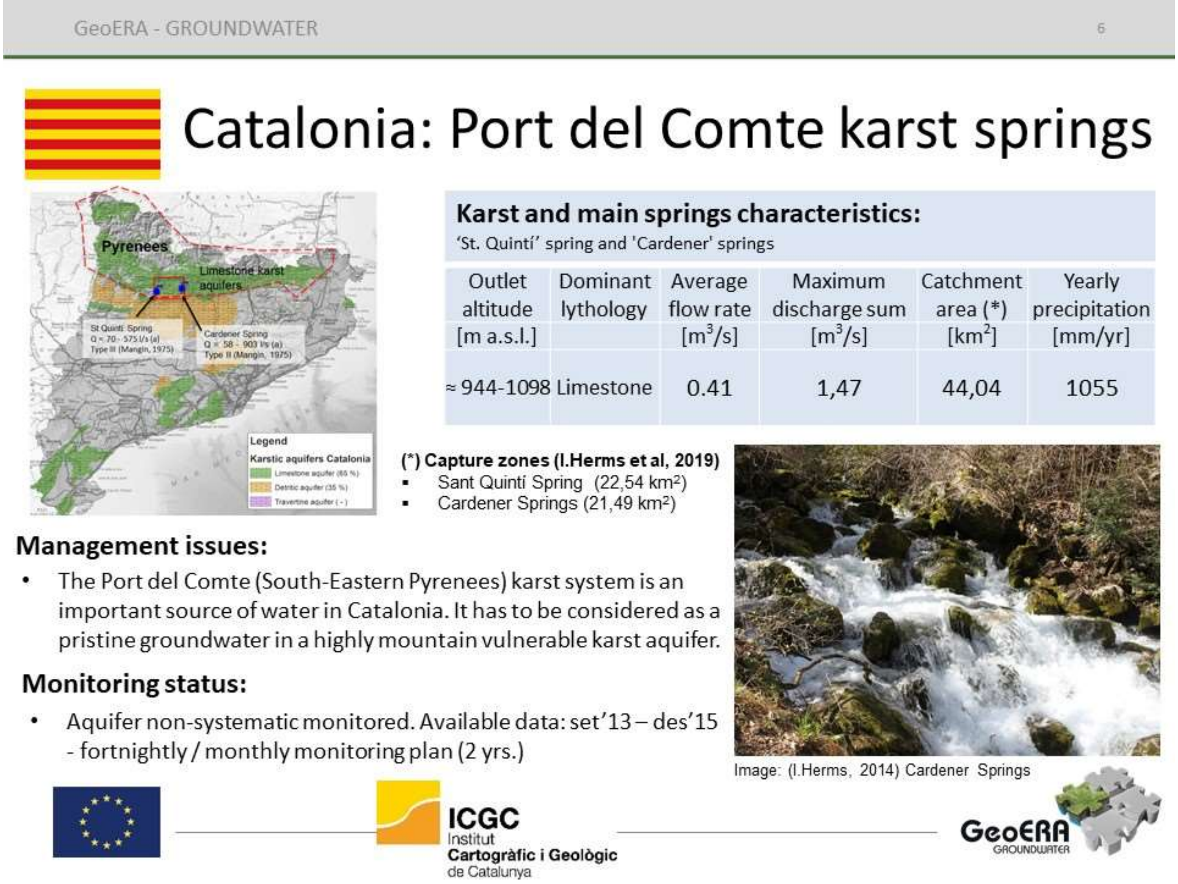

Catalonia: Port del Comte karst springs

Karst and main springs characteristics:

'St. Quintí' spring and 'Cardener' springs

Outlet altitude [m a.s.l.]	Dominant lythology	Average flow rate [m^3/s]	Maximum discharge sum [m^3/s]	Catchment area (*) [km^2]	Yearly precipitation [mm/yr]
≈ 944-1098	Limestone	0.41	1,47	44,04	1055

(*) Capture zones (I.Herms et al, 2019)

- Sant Quintí Spring (22,54 km^2)
- Cardener Springs (21,49 km^2)

Management issues:

- The Port del Comte (South-Eastern Pyrenees) karst system is an important source of water in Catalonia. It has to be considered as a pristine groundwater in a highly mountain vulnerable karst aquifer.

Monitoring status:

- Aquifer non-systematic monitored. Available data: set'13 – des'15 - fortnightly / monthly monitoring plan (2 yrs.)

Image: (I.Herms, 2014) Cardener Springs

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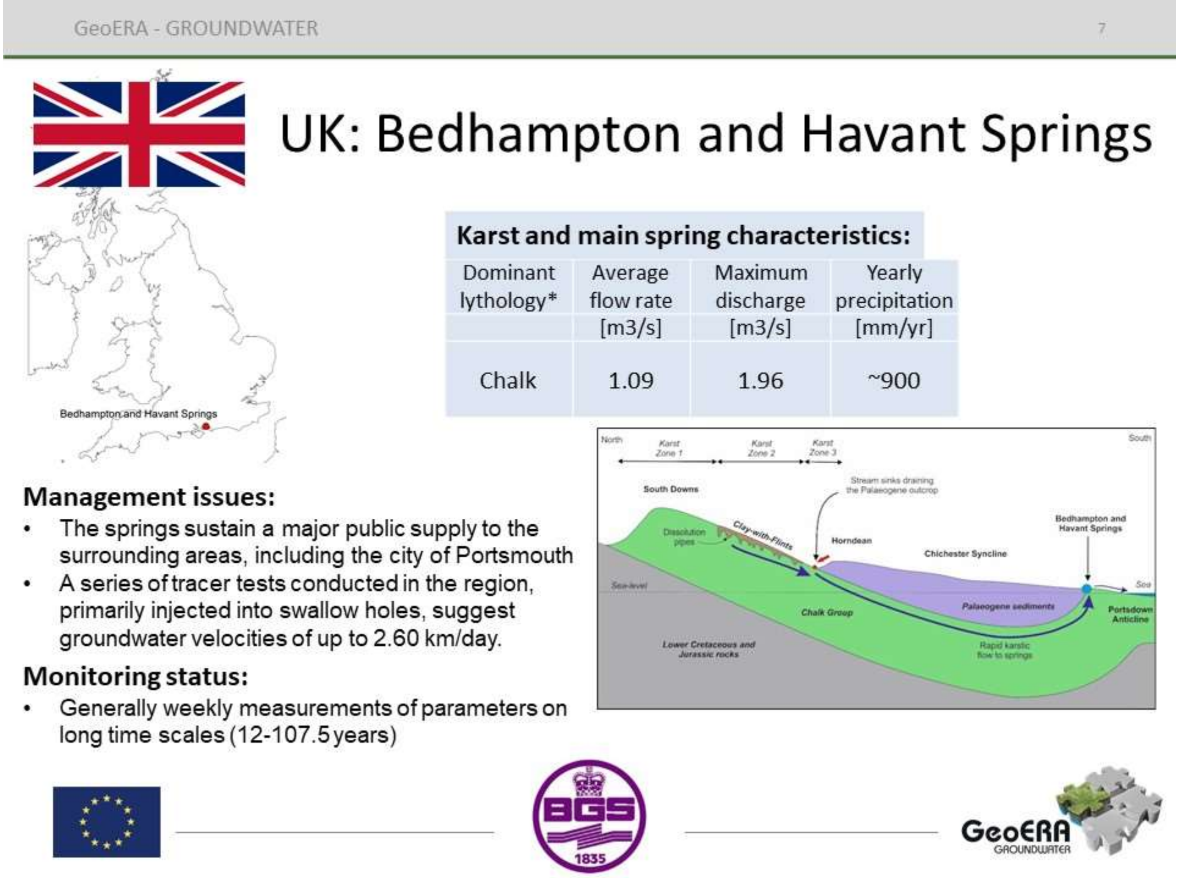
GROUNDWATER



UK: Bedhampton and Havant Springs

Karst and main spring characteristics:

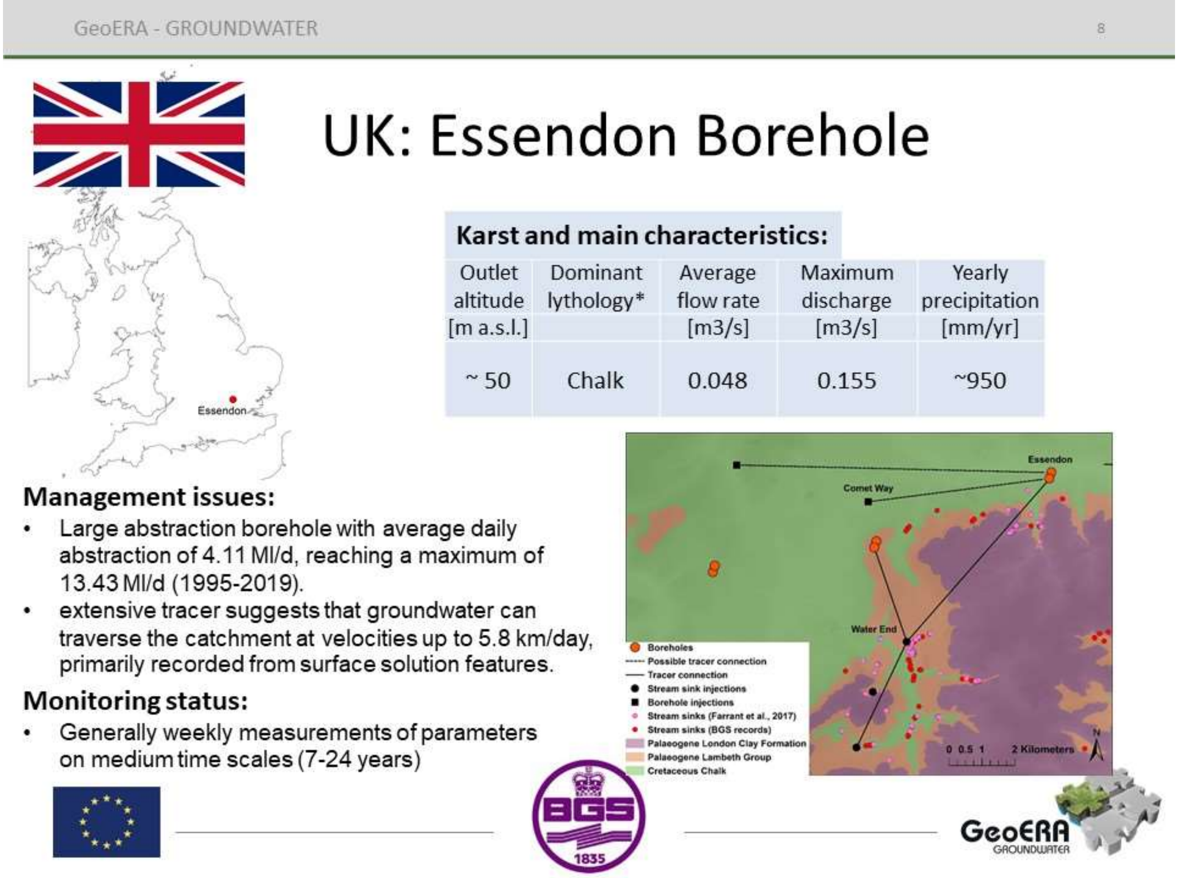
Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Yearly precipitation [mm/yr]
Chalk	1.09	1.96	~900

Management issues:

- The springs sustain a major public supply to the surrounding areas, including the city of Portsmouth
- A series of tracer tests conducted in the region, primarily injected into swallow holes, suggest groundwater velocities of up to 2.60 km/day.

Monitoring status:

- Generally weekly measurements of parameters on long time scales (12-107.5 years)



UK: Essendon Borehole

Karst and main characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Yearly precipitation [mm/yr]
~ 50	Chalk	0.048	0.155	~950

Management issues:

- Large abstraction borehole with average daily abstraction of 4.11 Ml/d, reaching a maximum of 13.43 Ml/d (1995-2019).
- extensive tracer suggests that groundwater can traverse the catchment at velocities up to 5.8 km/day, primarily recorded from surface solution features.

Monitoring status:

- Generally weekly measurements of parameters on medium time scales (7-24 years)

Slovenia - Italy: Classical Karst Aquifer

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
1	Limestone	30	130	500	1500

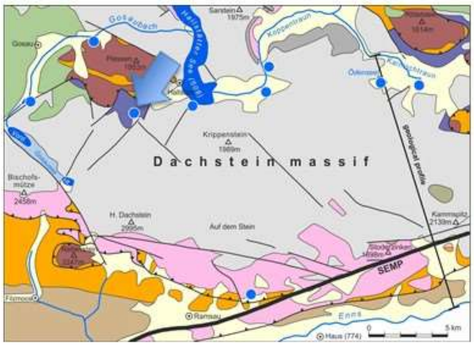
Management issues:

- Crossborder aquifer protection area
- Increasing urban and industrial pressures at the aquifer's recharge area
- Bacterial and turbidity pollution during high flow conditions

Monitoring status:

- Slovenian National groundwater monitoring
- Monitoring of water supply companies
- Research monitoring of GeoZS and University of Trieste

Austria: Waldbach spring (Dachstein region)



Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lithology*	Average flow rate [m^3/s]	Maximum discharge [m^3/s]	Catchment area [km^2]	Yearly precipitation [mm/yr]
920	Limestone	3,5	32	30	2.500

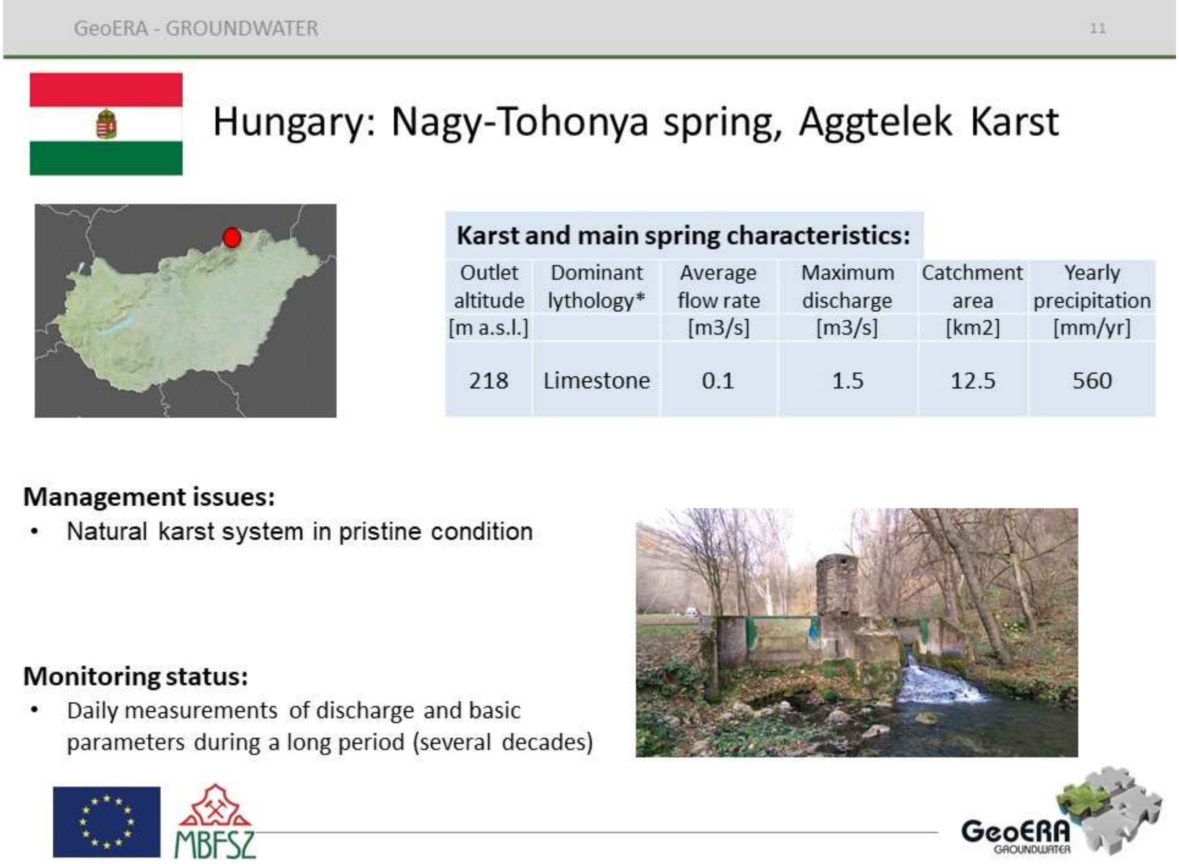
Management issues:

- Major spring near Hallstatt that belongs to the Dachstein Massif. Use: hydroelectric power (approx. 4 Megawatt per year) and springs nearby for the water supply of Hallstatt.

Monitoring status:

- systematic monitoring of discharge since 1970s.

Waldbach spring outlet



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Hungary: Nagy-Tohonya spring, Aggtelek Karst

Karst and main spring characteristics:

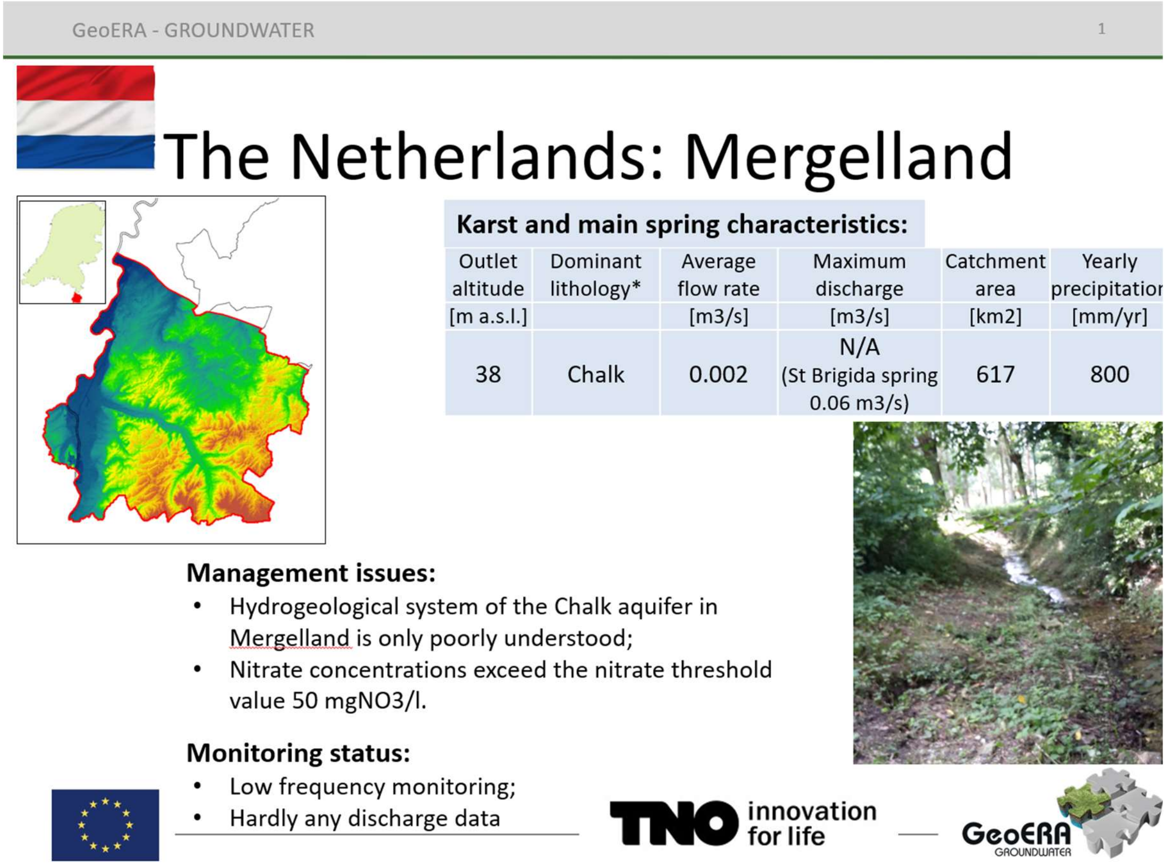
Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
218	Limestone	0.1	1.5	12.5	560

Management issues:

- Natural karst system in pristine condition

Monitoring status:

- Daily measurements of discharge and basic parameters during a long period (several decades)



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The Netherlands: Mergelland

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lithology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitatior [mm/yr]
38	Chalk	0.002	N/A (St Brigida spring 0.06 m3/s)	617	800

Management issues:

- Hydrogeological system of the Chalk aquifer in Mergelland is only poorly understood;
- Nitrate concentrations exceed the nitrate threshold value 50 mgNO3/l.

Monitoring status:

- Low frequency monitoring;
- Hardly any discharge data

GeoERA - GROUNDWATER 1

Romania: Moneasa karst springs

Karst and main spring characteristics:

Outlet altitude [m a.s.l.]	Dominant lythology*	Average flow rate [m3/s]	Maximum discharge [m3/s]	Catchment area [km2]	Yearly precipitation [mm/yr]
320	Limestone	0.15	0.9	66	939

Management issues:

- Moneasa Resort offers spa treatments based on the hypothermal waters of the Grota Ursului karst system.

Monitoring status:

- Aquifer non-systematic monitored. Available data: oct'97 – dec'88 – daily data (1 yr.)